UNCLASSIFIED DTIC FILE COPY

SECURITY CLASSIFICATION OF THIS PAGE

(2)

REPORT DOCUMENTATION PAGE

1a. RE	1b. RESTRICTIVE MARKINGS
2a. SE AD-A201 021	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. D	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFOSR-TR- 88-1168
6a. NAME OF PERFORMING ORGANIZATION: Indiana University / 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION: AFOSR/NL
6c. ADDRESS (City, State, and ZIP Code) Bloomington, IN	7b. ADDRESS (City, State, and ZIP Code) Bldg. 410 Bolling AFB, DC 20332-6448
8a. NAME OF FUNDING/SPONSORING ORGANIZATION: AFOSR / 8b. OFFICE SYMBOL (If applicable): NL	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER AFOSR-87-0089
8c. ADDRESS (City, State, and ZIP Code) Bldg 410 Bolling AFB, DC 20332-6448	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO.: 61102F; PROJECT NO.: 2313; TASK NO.: A5; WORK UNIT ACCESSION NO.:

11. TITLE (Include Security Classification)
Institute for the Study of Human Capabilities

12. PERSONAL AUTHOR(S)
Dr. Watson

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Annual	FROM 1 Aug 87 TO 31 Jul 88	Aug 88	51

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This annual report of the Institute for the Study of Human Capabilities describes work in several areas, all of which focus on problems of skilled human performance. The Institute's investigators are primarily active in the fields of sensory processes including vision, audition, and touch, and in human cognition and decision making; research in those areas is the major content of this report.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	Unclass

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL
John Tangney	(202) 767-5021	NL

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

88 10

AFOSR-TR- 88-1168

Technical Report

Summary Descriptions of Research
for the period
January 1987 through August 1988

Institute for the Study of Human Capabilities

Speech and Hearing Sciences 104
Indiana University
Bloomington, Indiana 47405

Annual Technical Report

Summary

An Institute for the Study of Human Capabilities has been founded at Indiana University. The Institute currently consists of eleven affiliated laboratories, in which research is conducted by 15 faculty investigators and a considerably larger number of graduate research assistants, technicians, programmers, and other staff members. One of the primary purposes of the Institute is to provide enhanced opportunities for interactions among these investigators, whose departmental appointments are in six departments (Psychology, Speech and Hearing Sciences, Visual Science, Linguistics, Mathematics, Medical Science) and three schools or colleges (College of Arts and Sciences, School of Optometry, School of Medicine) of the University. Another purpose is to familiarize scientists experienced in basic research on sensory processing and decision making with current problems in the field of human engineering, to which their fundamental research may be applicable. Last, the Institute is intended to serve as a source of technical or scientific advice for researchers in government or industry, who are working in areas related to those represented in our laboratories.

We have made significant progress toward these goals, first through the purchase and installation of an inter-laboratory computer network, consisting of Apollo workstations. That system has been brought into operation over the past year and is now in regular use for the exchange of information and, in several laboratories, for data analysis, graphics, and modeling. Another way that the institute-affiliated faculty interact is by attending institute-sponsored seminars presented by visiting scientists, and through other interactions with these visitors. Funds made available through the institute have also been used to construct new research apparatus in several laboratories. Finally, the Institute has employed several part-time technicians, programmers, and graduate student research assistants to conduct research under the direction of the faculty investigators. One full-time systems programmer has been employed, whose efforts are distributed between a research project in color vision and support of the inter-laboratory computer network.

By these means the Institute has provided partial support of research leading to the publication of [15?] articles in scientific journals, and the presentation of [47?] papers at meetings of scientific societies. The Institute has supported travel by faculty investigators to Air Force research facilities where they participated in discussions of current research projects. Institute investigators gave a series of research presentations to scientists visiting from Wright-Patterson Air Force Base.

TABLE OF CONTENTS

SOURCES OF SUPPORT

In addition to the support provided by the Air Force Office of Scientific Research (#87-0089), individual research projects described in this report were supported by the following grants:

I Auditory Discrimination:

NIH NINCDS 50-335-12:	Discrimination and Identification of Auditory Patterns (includes clinical applications) - C.S. Watson
AFOSR 53-335-04:	Perception of Complex Auditory Patterns - C.S. Watson
NSF 48-335-01:	Indiana Speech Training Aid (ISTRA) - C.S. Watson
NWC N6053087M360D:	Human and Expert Decision Systems - C.S. Watson

II Tactile Discrimination:

NIH Cutaneous Pattern Perception 7/86 - 6/93 - J.C. Craig

NIH, Tactile Aid to the Deaf 11/86-11/88 (Creare, Inc. subcontracted to I.U.) - J.C. Craig

III Visual Discrimination

NIH (NEI) R01-EY5109	Functional analysis of retinal ganglion cells. - L.N. Thibos
NIH S07-RR5962	Biomedical Research Support Grant - L.N. Thibos

IV Mechanisms of Sonar Signal Production and Vocal Tract Acoustics of Echolocating Bats:

NSF BNS 82-17099

NSF BNS 85-19621

Additional support was provided by:

The Office of Research
and Graduate Development,
Indiana University

INTRODUCTION

This Annual Technical Report of the Institute for the Study of Human Capabilities describes work in several areas, all of which focus on problems of skilled human performance. The Institute's investigators are primarily active in the fields of sensory processes including vision, audition, and touch, and in human cognition and decision making; research in those areas is the major content of this report.

Specific projects examine the abilities of human subjects to use information obtained from visual, auditory, and tactual displays. Both empirical and theoretical studies have been conducted. The studies of human cognition include projects on machine aided detection and recognition, the integration of information from multiple observations, the automatization of decision making, and automatization as a way of overcoming attentional limitations. In hearing, studies include measures of the auditory system's dynamic range, the use of multiple invariant cues in recognition of acoustic signals, pattern discrimination abilities, optimal "packaging" of information in auditory patterns, and discriminability of noise samples. In addition, the development of a general model for complex pattern discrimination is proposed. In vision, projects include both theoretical and experimental studies of human color vision, including response of subjects to color video patterns. Additional studies examine peripheral vision and the identification of moving stimuli. Studies of the tactual sense include the development of a new tactual stimulator, measures of temporal masking and attention, and the study of higher order processes.

Current research projects in our laboratories include studies in the following categories:

I Auditory Discrimination: the psychophysics of auditory capabilities, the limits of auditory attentional capacity, the ability to discriminate signals composed of gaussian noise samples.

II Tactile Discrimination: development of tactile arrays, and interference in tactile localization.

III Visual Discrimination: human peripheral vision, human visual optics, spatial processing of color information, perception of moving objects, and color theory.

IV Mechanisms of Sonar Signal Production and Vocal Tract Acoustics of Echolocating Bats: sound emission patterns, predictive tracking of moving targets by echolocating bats, and the physiology of bird song.

V Cognition and Decision Making: perception of multidimensional complex sounds, multi-stage decision making, differences between visual and memory search, connectionist approaches to speech perception, use of fault trees, and computer-based instruction

Form and content of the reports. It is not our intention to provide sufficient information in the brief project descriptions included here so that any of this work could be replicated. We believe such detail is best reserved for the descriptions of the work that will be submitted to appropriate journals, and specifically discourage any citation of reports which, like these, have not been through the scrutiny of independent peer review. We do hope, however, that the early knowledge of research that is underway or that, because of publication lags, will not appear for some time in the open literature, may be of value to colleagues who are working in closely related areas. We encourage readers of these brief reports to write to individual investigators if further detail is desired on any of the projects. In some instances draft manuscripts are available, and we will do our best to provide whatever information is requested.

In general, our rule for inclusion of projects in this report is that they have yielded sufficient new information that we are able to offer a conclusion or two, however tentative those might be. Projects on the drawing board, or so recently underway that no conclusions can yet be proposed, have been reserved for subsequent reports.

Reprints. The bibliography at the end of this report lists articles by members of our research groups that have appeared over the past twenty months, a "window" that we will move forward in successive reports.

Whatever is creative in these reports typically reflects the joint intellectual efforts of investigators, research assistants, and many others who participate in the research projects. While we try to give credit where it is due, the ownership of initial ideas is often impossible to establish. We are only certain of who does the work involved in the collection and analyses of data, and who writes the final paper; those people are formally recognized through authorship, but often a "group as a whole" is as close as we can come to the source of the original ideas for an experiment or for forms of analysis or, most importantly, for a theory. It is a pleasure, at any rate, to work with colleagues who seem to have an inexhaustible reserve of new ways to think about interesting questions.

CSW

PERSONNEL

Investigators

Charles S. Watson, Ph.D., Director	Professor, Speech & Hearing Sciences part-time Professor, Psychology
James C. Craig, Ph.D., Associate Director	Professor, Psychology
Arthur Bradley, Ph.D.	Assistant Professor, Visual Sciences
S. Lee Guth, Ph.D.	Professor, Psychology and Visual Sciences
Larry E. Humes, Ph.D.	Professor, Speech & Hearing Sciences
Donald E. Robinson, Ph.D.	Professor, Psychology and Adjunct Professor, Speech & Hearing Sciences
Richard M. Shiffrin, Ph.D.	Professor, Psychology
Larry N. Thibos, Ph.D.	Assistant Professor, Visual Sciences

Associate Investigators

N. John Castellan, Jr., Ph.D.	Professor, Psychology
Diane Kewley-Port, Ph.D.	Assistant Professor, Speech & Hearing Sciences
Gary R. Kidd, Ph.D.	Assistant Scientist, Department of Speech & Hearing Sciences
Daniel P. Maki, Ph.D.	Professor, Mathematics
Conrad Mueller, Ph.D.	Professor Emeritus, Psychology
Robert Port, Ph.D.	Associate Professor, Linguistics
Roderick Suthers, Ph.D.	Professor, Medical Sciences

Research Assistants

Name	Degree	Laboratory
Bruce Berg	Ph.D.*	Auditory Research
Karen Campbell	M.S.	Medical Sciences
Frank E. Cheney,	O.D., M.S.	Visual Sciences
Gary Durrant	Ph.D.*	Medical Sciences

Name	Degree	Laboratory
Sue Fallon	B.S.	Auditory Research
Steven Gregory	B.A.	Visual Sciences
Troy Hackett	B.A.	Hearing & Communications
David J. Hartley	Ph.D.	Medical Sciences
Rebecca Schurr Hartley	M.S.	Medical Sciences
Christine Kapke	B.A.	Hearing & Communications
Jane Krietemeyer	B.A.	Hearing & Communications
Mary Kyle	B.A.	Hearing & Communications
Lisa Madden	B.A.	Hearing & Communications
Susanne Patterson	B.A.	Hearing & Communications
Martin Rickert	M.S.	Auditory Research
Laura Smith	B.A.	Hearing & Communications
David Still	O.D., M.S.	Visual Sciences
David J. Walsh	O.D., M.S.	Visual Sciences
Marcia Wilkins,	B.A.	Visual Sciences
Michael Wilkinson	M.S.	Visual Sciences
Ming Ye	B.S.	Visual Sciences
Xiaoxiao Zhang	B.S.	Visual Sciences

Technicians

Name	Degree	Laboratory
Mike Bailey		Auditory Research
Andrea Bergen	M.S.	Visual Sciences
Wes Brown		Hearing & Communications
Jerry C. Forshee	M.S.	Auditory Research
Kevin Haggerty	B.A.	Visual Sciences
Deborah Holland		Medical Sciences
David Link		Auditory Research
David Montgomery	ASEET	Hearing & Communications
Wancheng Wang	M.S.	Visual Sciences

* Personnel who have graduated or resigned during 1987-88.

EXTRAMURAL ACTIVITIES

C. Watson is the director of the Institute for the Study of Human Capabilities and serves as an advisor to the National Research Council's Committee on Hearing, Bioacoustics and Biomechanics (CHABA). He is currently chairman, CHABA Working Group 95, on Communication Aids for the Hearing Impaired. He is also a member of ASA Standards Committees 53-63 on Acoustical Warning Devices, and 53-76 on Computerized Audiometry. Watson serves as a reviewer for the *Journal of the Acoustical Society of America*, *Journal of Speech and Hearing Research*, and *Perception and Psychophysics*.

J. C. Craig is the Associate Director of the Institute for the Study of Human Capabilities. He serves as a member of special review panels of NSF, NIH, and SBIR as well as having been a member of the NIH Study Section on Sensory Disorders and Language. He is the recipient of the NIH's Javits Neuroscience Investigator Award, July, 1986 - June 1993.

A. Bradley serves as a scientific referee for Butterworth Publishers, *Vision Research*, *Journal of Neurophysiology*, *Journal of the Optical Society of America*, *Investigative Ophthalmology and Visual Science*, the *American Journal of Optometry and Physiological Optics*, and *Clinical Vision Research*.

N. J. Castellan, Jr. is the Associate Editor of *Computers and the Social Sciences*, and on the Editorial Boards of *Organizational Behavior and Human Decision Processes*, *Behavioral Decision Making*, and *Social Science Computer Review*.

S. L. Guth is an ad hoc member of the U.S. Committee of the International Commission on Illumination and a Fellow of the Optical Society of America. He is a referee for grant proposals submitted to NIH and NSF as well as a referee for articles submitted to *J. Opt. Soc. Amer.*, *Vision Research*, *Psych. Review*, *J. Exp. Psych.*, *Perception*, *J. Color Res. and Application*, *Perception and Psychophysics*, and *Science*.

L. Humes continues as a scientific advisor to CHABA and as editorial consultant or reviewer for the *Journal of the Acoustical Society of America*, *Journal of Speech and Hearing Disorders*, and *Ear and Hearing*. He is currently an Associate Editor of the *Journal of Speech and Hearing Research*. He is also a member of the Technical Committee on Psychological and Physiological Acoustics of the Acoustical Society of America. He continues to be supported, in part, by a Research Career Development Award from NINCDS.

D. Kewley-Port is Associate Editor for Speech Processing and Communication Systems of the *Journal of the Acoustical Society of America*. She also reviews manuscripts for the *The Journal of Speech and Hearing Research*, *Language and Speech*, and *IEEE Transactions on Acoustic, Speech and Signal Processing*.

G. Kidd reviews manuscripts for the *American Journal of Psychology* and the *Journal of Experimental Psychology: Human Perception and Performance*.

Daniel P. Maki is a member of the American Mathematical Society, the Society for Industrial and Applied Mathematics, and the Acoustical Society of America and is Governor of the Mathematical Association of America.

Robert F. Port is a member of the Linguistic Society of America, the Acoustical Society of America, the Association for Computational Linguistics, and the International Neural Network

Society. He reviews manuscripts for the *Journal of the Acoustical Society of America*, the *Journal of Speech and Hearing Research*, *Perception and Psychophysics*, and the *Journal of Phonetics*.

D. Robinson continues to serve as a scientific advisor to CHABA and on the Science Advisory Board of the Parmly Hearing Institute, Loyola University, Chicago. In the last year, he presented an invited lecture at The Central Institute for the Deaf, St. Louis, MO and served as an invited panel member at the annual meeting of the Hugh O'Brian Youth Foundation, DePauw University, Greencastle, IN. He has reviewed papers for the *Journal of the Acoustical Society of America*, the *Psychological Bulletin*, and *Developmental Psychobiology*.

R. M. Shiffrin serves on the governing boards of the Psychonomic Society and the Society for Mathematical Psychology and is a consulting editor for *Memory and Cognition*, and *Acta Psychologias*. In 1987 he was the chair of the governing board of the Psychonomic Society and the Acting Director of Indiana University's Cognitive Science Program.

R. A. Suthers is on the editorial board of *Experimental Biology* and is a reviewer for the *Journal of Comparative Physiology*, *Ethology*, *Animal Behavior*, *Science*, *Behavioral Ecology & Sociobiology*, and the *Canadian Journal of Zoology*. He has been the invited lecturer at numerous national and international symposia.

L. Thibos serves as editorial reviewer for the *Journal of the Optical Society of America*, the *American Journal of Optometry and Physiological Optics*, and *Vision Research* and as a grant reviewer for the Air Force Office of Scientific Research, the National Science Foundation, and the National Health and Medical Research Council of Australia. In March, 1986 he presented an invited lecture on visual information processing to the Institute of Electrical and Electronics Engineers (Indiana Chapter) and in September, 1987 he presented an invited lecture on quantum efficiency and performance of retinal ganglion cells at the symposium *Vision: Coding and Efficiency* in honor of Professor H.B. Barlow at the University of Cambridge, England. In December, 1987 he was elected Fellow of the American Academy of Optometry.

Auditory Discrimination

I. Psychophysics of Auditory Capabilities

Proportional target-tone duration as a factor in auditory pattern discrimination.
C. Watson, Kidd, and Washburne

The original goal of this research was to determine whether there is a combination of component durations and total pattern duration that would *optimize* information transmission for tonal patterns. The first experiments in this series used an adaptive-tracking procedure in which, for various total durations, the number of components per pattern was increased or decreased from trial to trial in a forced-choice discrimination task (Watson and Foyle, 1983). Patterns consisted of sequences of tones, randomly selected from a 300 - 3000 Hz range. As the number of components in the patterns varied, the duration of each of the individual components was always equal to the total duration divided by the number of components. The procedure was repeated in seven experiments, which differed in the nature of the discrimination task.

These studies identified two types of discrimination task. These types were distinguished by the way that performance was affected by changes in the number of components. One type included tasks requiring only the detection of changes in temporal structure. Performance in these tasks was determined by a critical duration. As pattern duration increased from 62.5 msec to 2 sec, the number of components for constant performance increased, simply depending on the number of 30 to 40 msec components that could be fitted into the total duration. The other type included tasks requiring the detection of changes in the pitch structure. For these tasks, the number of tones for $d'=1.0$ was nearly constant over the entire range of total durations.

One of the discrimination experiments that required detection of a change in the frequency of a single component was replicated, but with an adaptive procedure that tracked on $\Delta f/f$ rather than on the number of components. As before, listeners were tested under high-stimulus-uncertainty conditions with isochronous patterns ranging in duration from 62.5 msec to 2 sec. Results again revealed that thresholds were strongly dependent upon the number of components, and only weakly on total (or component) duration. For patterns with 1 to 3 components, discrimination performance approached that of previous measures of the resolving power of the auditory system. However, as the number of components was increased, discrimination thresholds increased by as much as 10 to 100 times for patterns with more than 7 or 8 components. In comparison, the effects of both absolute duration and component duration appeared to be quite small. Similar results were obtained with anisochronous patterns in which the target duration was still equal to the total duration divided by the number of components but the context-tone durations were varied randomly (Watson and Foyle, 1985).

These results were interpreted as implying an informational limit on pattern processing, a limit that appeared to be reasonably close to the "magical" 7 ± 2 (components in discriminable patterns). However, the constant-n results are also consistent with an alternative hypothesis, that target tones are equally well resolved if they occupy *equal proportional durations of the patterns in which they occur*. In other words, the proportion of a pattern of total length T that is occupied by one of *n* equal-duration components will be $1/n$, for all values of T.

To distinguish between these alternative explanations, a new experiment was run in which the number of components and the proportion of the total duration occupied by the target component were varied independently. For a given proportion of the total duration and a given total duration, as n increased, the target-tone duration stayed constant and the context-tone durations were shortened equally to fit within the total duration. Of course, at a given proportion of the total duration, all tone durations changed proportionately with changes in the total duration. But, if the proportion-of-the-total-duration hypothesis is correct, changes in either total pattern duration or in the number of components would not be expected to affect performance if proportional target-tone duration remains constant.

The design of the new experiment was a 3x3x3 factorial which included three total durations (100, 500, and 1500 msec), three target-tone proportions of the total duration (.10, .20, and .40), and three numbers of components (3, 5, and 9). In this experiment the target tone was always in the middle position and toward the middle of the pattern's frequency range (300 to 3000 Hz). A same-different discrimination task was used in which the frequency of the target tone was varied. Threshold $\Delta f/f$ was determined separately for each condition using an adaptive tracking procedure. Seven subjects participated in 8 one-and-a-half hour sessions for a total of 160 trials per condition.

Mean tracking values for the last 40 trials in each condition, plotted as a function of the target-tone proportion of the total duration, are shown by the dotted lines in Figure 1. These plots clearly show that the target-tone proportion of the total duration accounts for most of the variance, while n, total duration, and individual component duration account for very little. A small effect of total duration can be seen, primarily with the smaller proportions of the total duration (probably explained by the very brief target durations in these cases)

Since most of these patterns were anisochronous, with target tones ranging from about one fifth as long as context tones to about four and a half times longer than context tones, these data were compared to those from the earlier experiment (described above) with isochronous patterns (and variable n) to see whether the same relationship between performance and the target proportion of the total duration held in both experiments. Data from the earlier experiment are shown by the solid lines in Figure 1. It can be seen that the agreement between the isochronous and anisochronous conditions was quite good, indicating that differences in duration between target and context tones in anisochronous patterns did not facilitate discrimination.

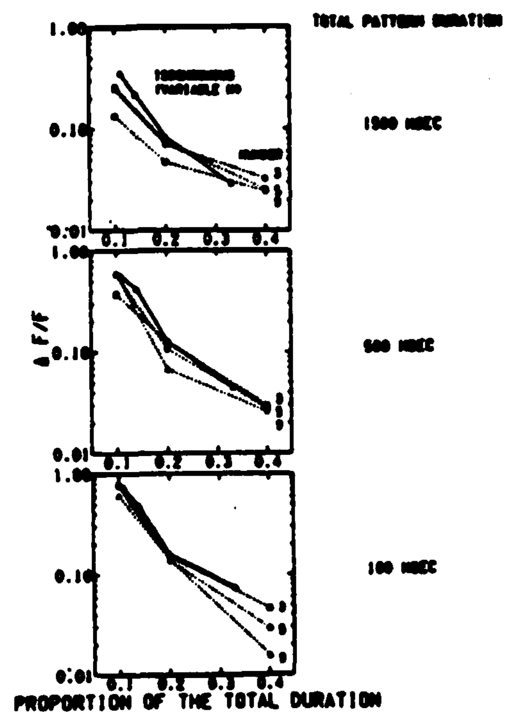


Figure 1

A second experiment was conducted to study the effects of changes in the target-tone proportion of the total duration and context-tone duration for specific target-tone durations. While neither target-tone duration nor context-tone duration appeared to account for much of the variance in the above experiment, a different (but overlapping) range of values for these variables was used with each target-tone proportion of the total duration. The second experiment was designed to test a wide range of target-tone and context-tone durations for different target-tone proportions of the total duration. Three target-tone durations (50, 100, and 200 ms) and two proportions of the total duration (.10 and .20) were used. Each target-tone duration was tested with four context-tone durations. Four ratios of context-tone duration to target-tone duration (C/T) were used (.25, .50, 1.00, and 1.50) with each target-tone duration. Total duration and number of components were determined by the combination of target-tone duration, proportion of the total duration, and C/T in each condition.

The results revealed a substantial effect of the target-tone proportion of the total duration for all target-tone durations and C/T ratios. The effect of PTD was greatly diminished at the smallest C/T ratio (.25) due to a large improvement in the PTD = .10 conditions at this C/T ratio. It appears that target-tone proportions of the total duration as small as .10 lead to poor performance unless context-tone durations are quite short in relation to target-tone durations (thus making the target tone more salient).

These results show that for a wide range of total pattern durations, numbers of components, component durations, and temporal structures, the detectability of pitch changes in tonal patterns is largely determined by the proportion of the pattern that has been changed and not by some limitation on the number of tones that can be processed. That a Weber's-Law-like relation determines component salience, as reflected in the proportional amount of the pattern that is varied, apparently means that these patterns are treated as wholes, rather than as sequences of tones that are independently processed. We have not yet conceived of a well-defined perceptual mechanism that would predict such a result. It is, of course, consistent with the well known Weber fraction for duration discrimination ($\Delta T/T \approx 0.1$), which appears to be valid for roughly the same range of durations as the proportional-duration rule.

Manuscripts and Abstracts

Watson, C. S., & Kidd, G. R. (1987). Proportional target-tone duration as a factor in the discriminability of tonal patterns. *Journal of the Acoustical Society of America, 82*, Suppl. 1, S40.

Watson, C. S., Foyle, D. C., & Kidd, G. R. Limited processing capacity for auditory pattern discrimination. (manuscript in preparation).

Kidd, G. R., & Watson, C. S. Proportional target-tone duration as a factor in the discriminability of tonal patterns. (manuscript in preparation).

Detection of pattern repetition in continuous tone-patterns.
C. Watson, Kidd, Washburne.

Additional data have been collected in experiments designed to test listeners' abilities to detect the repetition of multi-tone patterns as a function of tone duration and number of tones in the pattern. These experiments are variations on those reported by Guttman and Julesz (1963,

Journal of the Acoustical Society of America), but using tonal sequences rather than noise samples. Subjects are presented with repeating or non-repeating tone patterns using a tracking paradigm that increases or decreases the number of tones in a pattern depending on a subject's performance. Nine subjects have now been tested in an experiment utilizing 50-msec or 200-msec tones with ⅙-octave or 1-octave pattern bandwidths (centered on 1000 Hz). The data show strong effects of tone duration and bandwidth, as well as a significant interaction (due to a slightly greater effect of bandwidth at the 50-msec tone duration). The mean number of components for the 9 subjects for each condition is shown in Table 1. Listeners were able to detect the repetition of patterns consisting of more tones with the shorter tone duration and the wider bandwidth. The effect of tone duration is not simply an effect of total pattern duration: subjects are able to detect the repetition of patterns with longer total durations (but fewer tones) at the 200-msec tone duration.

Table 1. Mean number of tones for 70% correct detection of repetition (total duration of detectable repeating patterns, in seconds, shown in parentheses).

	Tone Duration	
Bandwidth	50ms	200ms
⅙ octave	62.9 (3.16)	30.7 (6.14)
1 octave	94.1 (4.71)	35.5 (7.10)

Despite our attempts to minimize the occurrence of unique events, subjects' reports indicated that judgments were often based on the recurrence of particular events rather than detection of whole-pattern repetition. To further reduce the occurrence of unique events, a new version of this experiment was developed in which the sequences of pitches of consecutive tones approximated a sinusoidal series. Tones deviated randomly from strict sinusoidal variation by ±6%, and a single repeating pattern spanned three cycles. This procedure reduces the possibility of unique events by constraining adjacent tone relations while eliminating the problems of pattern-restart discontinuities and gross changes in pattern macrostructure. Results obtained with this procedure suggested that unique events were still being used as a basis for repetition judgments. To date, our attempts to devise a class of tonal sequences for which listeners must attend to the microstructure of an entire sequence to detect the repetition of a series of tones within a sequence have not been successful.

Perception of salient auditory events or figures.
C. Watson, Kidd, Washburne.

We are continuing to use our auditory figure-identification procedure to study factors that may be systematically related to the emergence of auditory figures or "targets" from various backgrounds.

Response latency and decision criterion in psychophysical decisions.
Espinoza-Varas, C. Watson, Patterson, Kyle.

A manuscript has been prepared for submission to *Perception and Psychophysics* describing earlier data on the effects of decision criterion on the response latencies in psychophysical decisions. The response latency to a given stimulus was found to vary inversely with the distance between the stimulus and the current response criterion, and with the probability of the response. These effects were observed for both visually presented two-digit numbers and pure tones under three different decision tasks. (Experimental work supported by an NIH grant to the Central Institute for the Deaf. Manuscript preparation supported by NIH and AFOSR grants to Indiana University).

Development of norms and factor analysis of TBAC performance obtained in 398 listeners.
Espinoza-Varas, C. Watson, Symanski.

Since first developed (Watson et al., *J. Acoust. Soc. Am.* 1982, 71, S73), the Test of Basic Auditory Capabilities, TBAC, has been administered to approximately 600 listeners, in 10 different studies carried out at the Boys Town National Institute, the University of Nebraska, Lincoln, University of Wisconsin, Madison, and the Speech and Hearing Center, Indiana University. This large data base offers a unique opportunity to standardize and develop norms for the TBAC and to perform factor and cluster analyses. We have recently consolidated the data from the various studies, which were previously stored in several different formats and media. We have developed a coherent structure for this data base and currently have TBAC results for 398 listeners entered in the CDC-856 Indiana university computer, which has available appropriate statistical packages. Preliminary analyses have confirmed that the TBAC is a very reliable test. Figure 2 shows a comparison of average percent correct on the eight subtests obtained in 6 different studies employing normal listeners tested in the field (solid lines) and under headphones (dashed lines).

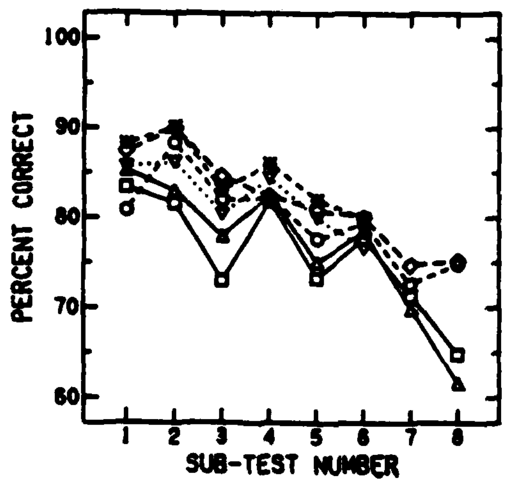


Figure 2

Perception of complex auditory patterns by humans.
Espinoza-Varas, C. Watson.

A chapter on pattern perception by humans was contributed to the book "The comparative psychoacoustic of complex acoustic perception," co-edited by S. Hulse and R. Dooling (Lawrence Earlbaum Associates, N.J.). The main thesis proposed in this chapter is that, for the case of mammals, measured phylogenetic differences in pattern perception ability would result more from differences in information processing abilities (i.e., central factors), than from structural and/or physiological differences in the peripheral auditory system. The book is currently in press.

Relations between auditory capabilities and phoneme perception.
Espinoza-Varas, C. Watson, Srygler.

A manuscript describing this work is in preparation for submission to the *Journal of the Acoustical Society of America*.

Interaural comparison of discrimination abilities in monaural hearing impaired listeners.
Espinoza-Varas, C. Watson.

We continue to collect data to compare, interaurally, the discrimination abilities of monaural hearing impaired listeners. The goal is to assess the differential roles of central and peripheral processing in speech and non-speech tasks.

Discriminability of noise samples.
Robinson, Fallon, Rickert.

Our work on the discriminability of noise samples continues. This work employs pairs of complex auditory waveforms that listeners are asked to discriminate. The waveforms are samples of broad-band, white, Gaussian noise. All experiments made use of a same-different paradigm. Research reported in previous years has investigated several parameters that affect the discriminability of noise samples. In our initial work in this area, we demonstrated that if only a small segment of a noise burst is replaced with a new sample of noise, the temporal position of the new segment is of critical importance in determining discriminability. Independent of total burst duration, changes made at the end of a burst are more discriminable than those in the middle, which are more discriminable than changes made at the beginning. In that work, we also observed a 'Weber's law' relationship between the duration of the altered segment and total burst duration. As total burst duration was varied from 25-msec to 150-msec, the ratio of the duration of the altered segment to total burst duration remained constant within each of the three conditions: beginning, middle, and end. In two additional experiments, we investigated the effects of decorrelating the noise samples on "different" trials. This was done in two ways: first, by time delaying the noise presented in the second interval relative to that in the first interval and, second, by adding an independent sample of noise to the sample presented in the first interval to generate the sample presented in the second interval. In both cases, increasing the correlation of the samples in the two intervals reduces discriminability. However, the functions relating performance to correlation are different depending on the method used to vary the correlation. In other work, we have attempted to improve performance by reducing the size of the set of noise samples presented to the subjects. We found a negligible effect of set size. In Progress Report

No. 2, we reported on the effects of introducing temporal gaps in the noise bursts. In the last year, we have extended the work on temporal gaps and have investigated the effects of reducing the level of portions of the noise bursts.

A. *Effect of gap duration and position.*
Robinson, Fallon.

In this experiment, the overall duration of the bursts of noise in a pair was 150 msec and either a 25-msec segment of new noise was inserted at the end of the burst or a 50 msec sample was appended to the beginning of the burst. A silent interval or gap replaced a portion of the repeated segment either immediately following or immediately prior to the appended segment. The duration of the gap was gradually increased until only 5-msec of the repeated or inserted segment remained. Although discriminability increased as gap duration increased, the presence of a brief repeated segment temporally separated from the appended segment by 90-120 msec caused a large decrement in performance. For example, when each burst in a pair consisted of a 5-msec repeated segment followed by a 120-msec gap and a 25-msec appended segment, the average P(C) is 0.72. If the 5-msec repeated segment was not present and the pair of 25-msec bursts was presented in isolation the overall P(C) increased to 0.88. It would appear, then, that interactions occurring after such a long silent interval are unlikely to be due to peripheral sensory interactions, as was suggested by Hanna (*Perception & Psychophysics*, 36, 409-416, 1984).

B. *Effect of varying the level of the repeated segment.*
Robinson, Fallon.

The effects of decreasing the level of the repeated segment on the discriminability of pairs of 150-msec bursts of noise was examined in two conditions. In the first condition a 15-msec sample of new noise was appended to the end of the second sample of pairs presented during "different" trials. A 75-msec sample of new noise was inserted at the beginning of the second sample of a pair in the second condition. Prior to varying the level of the repeated segment, the discriminability of the bursts presented in the two conditions was similar. Discriminability tended to gradually increase as the level of the repeated segment was decreased. Performance did not greatly improve until the level of the repeated segment was reduced from 50 to at least 28 dB SPL, suggesting that peripheral masking cannot account for the effect of the temporal position of the appended or inserted segment of noise on discriminability.

C. *Discriminability of noise samples: Dichotic presentations.*
Robinson, Rickert.

The main goal of this experiment was to investigate whether the factors that affect performance for diotic presentations act in a similar fashion when there are interaural differences. In the experiments described above (Robinson and Fallon), all stimuli were presented diotically, and thus there were no spatial cues. There are several binaural phenomena (e.g., the precedence effect) which suggest that interaural differences which occur at the beginning of an acoustic event may be more effective cues than those occurring later. Thus, it is possible that the large advantage of the "end" condition found with diotic presentations might not be found with dichotic conditions. With dichotic presentations, decreasing the proportion of common noise in one ear relative to the opposite ear generates a spatial cue for the listener. Although the position of the

binaural image of the noise remains centered, the noise becomes more diffuse in the region of the medial plane. Thus, the task for listeners in this study was to discriminate a pair of noise samples that varied in their spatial "compactness."

In order to allow comparison with our previous work, we used a two-interval, same-different task. The duration of the reference and the comparison sample was fixed at 150 msec. The spectral density of the noise was 50 dB SPL/Hz. The interaural correlation of the reference stimulus was equal to unity. Thus, on same trials subjects heard a diotic sample of noise twice. A new reference stimulus was generated at the beginning of each trial. On different trials interaural correlation was reduced by replacing a temporal segment of the noise in either the right or left ear with a statistically independent sample of noise. Four durations of the independent noise segment were used: 10, 25, 50, and 150 msec. The new, independent segment of noise was either placed at the beginning, in the middle, or at the end of the comparison sample.

Results for dichotic conditions were consistent with those for the previously reported diotic condition: discrimination performance is a monotonic increasing function of the duration of the uncorrelated segment of noise. Thus, for each temporal position, performance improves as the duration of the interaurally uncorrelated segment increases. Further, the ordering of performance for the three temporal positions is also the same: independent samples placed at the end are more discriminable than those in the middle which are more discriminable than those at the beginning. For example, a 10 msec independent segment at the end yields an average value of P(C) of 0.85. When the 10-msec segment is placed in the middle, P(C)=0.73. But, P(C) is only 0.68 when the 10-msec segment occurs at the beginning. Finally, there is a significant advantage in the dichotic conditions compared to the diotic ones. For example, if the independent segment is presented dichotically at either the beginning or middle of the sample, the duration of the segment required for P(C)=0.75 is approximately 80 msec less than that required for diotic presentations. A difference of 50 msec is required to equate performance when the independent segment is placed at the end of a burst. Thus, uncorrelated segments that occur at the end of a sample, presented either diotically or dichotically, are more discriminable than those occurring either in the middle or at the beginning of the burst of noise. Current models of binaural processing cannot account for these results.

Information integration: Multiple observations and internal noise.
Robinson, Berg.

The work described in this section began with two major goals. The first is to understand the processes by which humans integrate information over time or over channels. The "multiple look" problem is the basis for our initial work in this area. The basic question is, "How much additional information is gained by allowing observers more than one observation in a detection or discrimination task?" The second goal is to develop and evaluate models of "internal noise." The amount and rate of improvement in performance with an increasing number of observations will depend not only on the amount of internal noise, but also on the level of processing at which the internal noise is added.

The effects of modulating the frequency of one or both partials of two-tone complexes, on the relative dominance of the periodicity pitch of the complex were studied. The 0.5 sec complexes consisted of the 4th and 5th harmonics f4, f5, of fundamentals centered at 100, 250, 350, and 500 Hz and were presented at 45 dB SPL. The frequency of the partials was modulated unidirectionally by a single cycle of a linear ramp with positive slope. The depth of modulation, expressed as percent frequency change of the partials df%, varied from 0 to 60%.

The modulation of the partials was either coherent or perfectly correlated, with equal values of df% for both partials; or it was incoherent or uncorrelated by variable amounts, with different values of df% for each of the partials. In a pitch identification task, listeners decided whether the periodicity pitch of the complex, or the spectral pitch of the higher partial was the dominant impression associated with the stimulus. When the partials are modulated *incoherently*, differences in percent modulation between the partials greater than 3.5% to 6.0% are sufficient to prevent the integration of partials and make the spectral pitch of the higher partial dominant over the periodicity pitch of the complex. When the partials are modulated *coherently*, the percent modulation required to shift the pitch dominance from periodicity to spectral is greater than 22-27%. The values of df% at which the dominance changes from periodicity to spectral pitch are essentially independent of the fundamental frequency of the stimuli. The effects of frequency modulation on the integration of partials seem to be mediated, at least in part, by the changes in stimulus envelope periodicity induced by modulation. Coherent modulation, at small values of df% preserves the envelope periodicity and promotes the integration of partials. Incoherent modulation at small df% values, or coherent modulation at large df% values, both work against keeping a constant envelope periodicity and thus promote the segregation of partials. (Experimental work supported by NSERC grant to McGill University. Data analysis and manuscript preparation supported by NIH and AFOSR grants to Indiana University).

Previous research has demonstrated that performance in signal-in-noise detection tasks improves as listeners are allowed more observations. According to signal detection theory, d' increases as the square-root of the number of observations. This result assumes that the decision statistic is the mean of the n likelihood ratios (or any monotonic transformation of the likelihood ratios) obtained from the n observations. In some versions of the derivation, internal noise is assumed to be added prior to the formulation of the decision statistic. This assumption is made in order to account for the less than optimal performance observed at $n=1$, but does not alter the square-root-of-n prediction. Previous research has supported the square-root-of-n prediction. However, the earlier work provided only a limited test, since n never exceeded six. Our research has extended this work by using several paradigms and a greater number of observations.

Much of our work has involved the following paradigm. There are two probability density functions on frequency, one with a mean of 1000 Hz, one with a mean of 1100 Hz, and both with a common standard deviation of 100 Hz. On each trial, n independent samples are selected from one of the distributions and presented sequentially as n, 50-msec tone bursts, separated by 50 msec silent gaps. The listener's task is to decide from which of the two distributions the n-tones were sampled. Results reported in Progress Report No. 2 show that listeners can approach the theoretical d' for $n=1$, but do not follow the square-root-of-n rule, even for small n.

In order to account for the failure to obtain the square-root-of-n prediction, we have assumed an additional source of internal noise. This source is assumed to occur after the formation of the decision statistic. This type of internal noise may be thought of as additional variance introduced by uncertainty of the decision criterion, changes in response bias, or memorial factors associated with the decision statistic. Briefly, then, in the "partitioned variance" model, as we have termed it, internal noise is added at two stages: (1) at the periphery, before a decision statistic is formed and (2) centrally, after the statistic is formed. As we have previously reported, the model does an excellent job of describing the data of the sequential tone experiment, as well as those of a similar experiment in which the tones are presented simultaneously. Our work over the last year has concentrated in examining in more detail the sources of variability (internal noise) and in developing more detailed tests of the partitioned variance model.

Distribution of internal noise over the tonal sequence. An important question raised by our general model is whether information from each tone in a tonal sequence is equally weighted in determining an observer's decision. We have developed a technique for assessing how internal noise is distributed over the n–elements of a tonal sequence. In terms of the model, the amount of information obtained from different tones in an n–element sequence will be reflected in the variance of the internal noise added at each temporal position. If a particular temporal position contributes little to the final decision, that position will be found to have a large amount of internal noise associated with it. If, on the other hand, a particular element contributes a great deal, that element will have less internal noise associated with it. Data from an auditory experiment were analyzed to assess how internal noise is distributed over successive temporal positions. Over many thousands of trials we store the frequency of the tones actually presented in the ith temporal position (i = 1, 2, ... n; where n is the number of tones in the sequence). We then partition these stored frequencies into bins of arbitrary width. The purpose of this analysis is to keep track of the number of trials on which the frequency of the ith element was in each frequency bin. For each bin and each temporal position, we then compute the probability that the subject responds that the sequence came from the lower distribution. Cumulative normal distributions are then fit to the resulting ogives. The standard deviation of the best fitting normal distribution is then an estimate of the standard deviation of the total internal noise limiting performance at each display position.

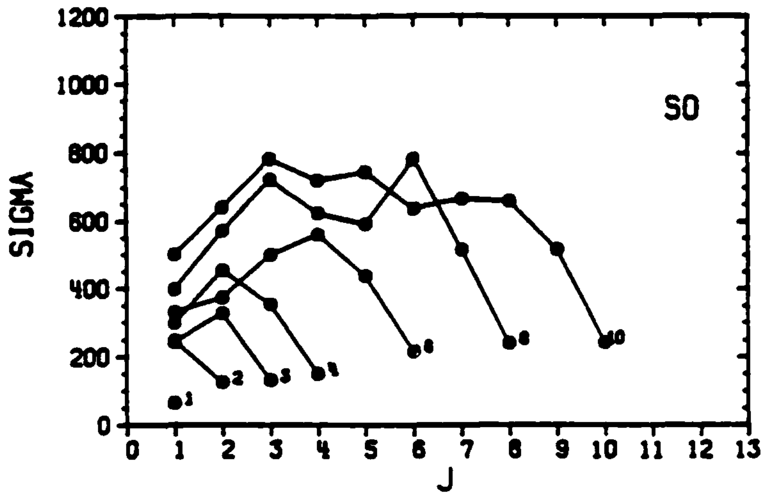


Figure 3

Figure 3 shows the standard deviation of the internal noise as a function of temporal position. The parameter on the figure is the total sequence length, *n*. If each element in the sequence contributed equally to the final decision, the lines in Figure 3 would be horizontal. It is clear that, for this subject, the last tone in a sequence contributes more to the final decision than do tones in the middle, which contribute less than those near the beginning of the sequence.

Portions of the work reported here have been reported. [Robinson and Berg (Math. Psych. Conf., Cambridge, MA, 1986), Berg and Robinson (JASA, 81, S33, 1987), and Sorkin, Robinson, and Berg (Proc. 31st Meeting Human Factors Soc., V.2, 1184–1188, 1987].

II. SPEECH PERCEPTION

Effects of stimulus uncertainty on category boundaries.
Kewley-Port, C. Watson, Foyle, Hackett.

Following the publication of our research on categorical perception, Richard Pastore submitted a letter to the editor of *J. Acoust. Soc. Am.* which criticizes our manuscript on several accounts. We are in the process of preparing a reply to his letter which will be reprinted in the same issue of the Journal within the next few months. While many of Pastore's arguments focused on his own earlier theoretical statements concerning categorical perception, some of them concerned the sparse data points in our Figures 3 and 4 (p. 1137) which displayed results from a VOT discrimination experiment, conducted under minimal-stimulus uncertainty. Since this issue, unlike some of the theoretical fine points, is readily evaluated in empirical terms, an additional experiment was conducted.

Results from a standard ABX discrimination task with a /ba–pa/ continuum ranging from 5 to 65ms in VOT are shown in the upper panel of Figure 4 (labeled "C"), along with corresponding results from Kewley-Port et al. (1988)(labeled "B"). Results from the original and replicated experiment are almost identical. In a same-different, minimal-uncertainty task, new data were collected for 10-ms or 5-ms VOT pairs. These data (labeled "C") all demonstrate high discrimination performance, but stop far short of a categorical "peak". In fact, if these data points are converted to a Weber ratio, the ratios for the 15–25 pair, 0.27, and for the 25–35 pair, 0.18, correspond closely to the values obtained earlier for the noise-buzz pairs (0.25 and 0.18 respectively) shown in Fig. 10 of Kewley-Port et al., 1988.

These results are entirely consistent with both the data and the conclusions presented in Kewley-Port et al. (1988), and fail to fulfill the dire predictions made by Pastore (that there may be a "sneaky peak" lurking between the data points). In particular, discrimination of temporal onsets for speech and non-speech stimuli appear to (a) be similar, and (b) follow common psychophysical laws. While categorical discrimination is the usual outcome of discrimination tasks employing high levels of stimulus uncertainty, and high cognitive loads, such results, at least for VOT and NLT continua, appear to be the result of a central level of auditory processing which is invoked when listeners have extensive familiarity with the stimuli and the categories with which they are to be identified.

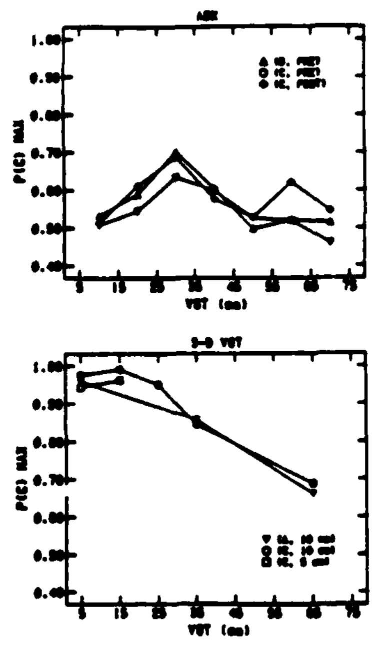


Figure 4

Manuscripts and Abstracts

Kewley-Port, D., Watson C.S. & Foyle D.C. (1988). Auditory temporal acuity in relation to category boundaries; speech and non-speech stimuli. *J. Acoust. Soc. Am. 83*, 1133-1145.

Watson, C.S. & Kewley-Port D. A reply to Pastore (1988), letter to the editor in preparation for *J. Acoust. Soc. Am.*

Psychoacoustic properties of isolated vowels

Detection of isolated vowels.
Kewley-Port, Hackett.

We have completed a series of experiments on the detectability of vowels in isolation. In previous progress reports, results for three sets of 10 vowels, one synthetic, one from a male talker and one from a female talker, were presented. Thresholds for detecting the vowels in isolation were obtained for several durations, ranging from 20 to 160 msec. Thresholds for vowels calibrated for equal sound pressure at the earphones differed by as much as 20 dB across vowels. However, the same patterns of thresholds obtained for the vowel set were obtained for all of the durations. The threshold pattern obtained for the 40-ms male vowels is shown in Figure 5.

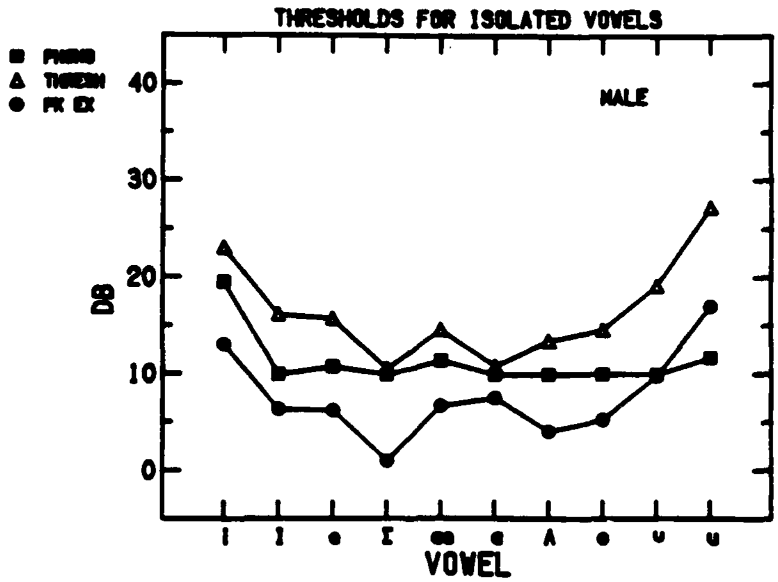


Figure 5

Several different analyses have been completed to attempt to explain the differential detectability for the various vowels within each set. The most detailed of these analyses involved a model developed by Moore and Glasberg for calculating excitation patterns (Moore and Glasberg, 1986; Moore and Glasberg, 1987). Excitation in this model is based on the sensation level of the Fourier components, relative to ISO thresholds. Using the model, an excitation pattern for each vowel was calculated from the FFT of the vowel, in which the amplitude of the harmonic for the highest spectral peak was calibrated to the threshold value obtained for a 40-ms vowel. The excitation pattern, the *specific loudness* pattern, the loudness in sones, and finally the loudness level in phons were calculated for each vowel.

If Moore and Glasberg's model can serve as a general model of the perception of loudness of complex sounds, as they have proposed, then our data suggest two hypotheses to test their model. The first is that vowels might be detected on the basis of the highest peak in the excitation function. The second was that the loudness level in phons was the basis for detectability. To determine whether either hypothesis was correct, the Peak of the Excitation (PK EX) value and the loudness level in phons (Phons), both in dB, were compared to the threshold patterns (in dBSPL) obtained, separately for each of the three vowel sets. Figure 5 compares the threshold values obtained for the male vowels with the corresponding values of PK EX and Phons. If either hypothesis fully explained the detectability of the vowel, then the modeled PK EX or Phon "thresholds" would, ideally, have a constant value in dB. That is, if the modeled thresholds were treated as a function, it should be flat. The closest any of the PK EX or Phon thresholds came to being flat for the three sets of vowels was the Phon data shown in Figure 5.

To determine how closely the modeled values came to the ideal, several statistics were calculated. To determine variability from a constant value, the range and standard deviation were calculated. To determine how flat the function was, the threshold values for each data set (obtained and modeled thresholds separately) were ordered from lowest to highest, a regression line was fit to the ordered values, and the *slope* of the regression line was obtained. The results of these analyses are shown separately for each data set in Table 2 below.

	Vowel Set											
Statistic	Synthetic			Male			Female			Average		
	Thresh	Peak Ex	Phons	Thresh	Peak Ex	Phons	Thresh	Peak Ex	Phons	Thresh	Peak Ex	Phons
Range	19.8	13.7	15.3	16.7	16.0	9.6	17.6	15.3	8.2	18.0	15.0	11.0
Sd	5.8	4.2	5.3	5.3	4.6	3.0	5.3	5.1	2.8	5.5	4.6	3.7
Slope	1.64	1.33	1.71	1.64	1.42	0.66	1.68	1.67	0.81	1.65	1.47	1.06

Table 2

Looking at range and standard deviation, modeled thresholds should be reduced compared to the obtained threshold values to support the hypotheses. The slope should also decrease, and approach zero to support the hypothesis of flat (i.e. constant) threshold values. For each vowel set, both modeled thresholds resulted in reduced values compared to the obtained thresholds. For the synthetic vowels, the Peak of the Excitation function model was better than the Phon model, but for the natural vowels from the male and female talker, the Phon model was best. In terms of absolute values of the statistics, the average values for all three data sets are shown at the right of the table. From these values, it appears that the loudness level in Phons provide the best model of the threshold values for the vowel sets tested.

References

Moore, B. & Glasberg B. (1986). The role of frequency selectivity in the perception of loudness, pitch and time. In B. Moore (Ed.), *Frequency Selectivity in Hearing*, (Academic Press: New York), 251-264.

Moore, B. & Glasberg B. (1987). Formulae describing frequency selectivity as a function of frequency and level, and their use in calculating excitation patterns. *Hearing Research*, 28, 209-244.

Manuscripts and Abstracts

Kewley-Port, D. (1988). Detection of natural and synthetic vowels. (in preparation).

Effects of response uncertainty on the intelligibility of nonsense syllables.
Espinoza-Varas, C. Watson, C. Parks.

The CUNY Nonsense Syllable Test (Dubno, J.R. and Levitt, H. J. Acoust. Soc. Am., 69, 249-261, 1981) uses a response format in which the number of response alternatives within each subtest is equal to the number of alternative stimuli: on each trial, the subject must choose the correct alternative from among 7-9 alternatives which are provided on an answer sheet. This response format might be less than ideal for several reasons. First, it depends on visual scanning and auditory-visual comparisons which may make the task somewhat more a cognitive one, and somewhat less a measure of auditory processing. Second, in a number of instances (e.g., prolonged testing) this response format seems unnecessarily burdensome to the subject. Finally, the errors or confusions are typically restricted to no more than 2-3 alternatives. The response densities for the remaining incorrect alternatives are often so low that they cannot be systematically ordered across the alternatives. We have developed a response format consisting of 3-alternatives: the correct alternative plus the two most likely confusions (as identified in Dubno's doctoral dissertation). The performance of 33 subjects tested in the 7-9 alternative format has been compared to that of 12 subjects tested in the 3-alternative format. Figure 6 shows the average percent correct identification for the 7-9 alternative (open symbols) and the 3 alternative format (solid symbols). With a few exceptions, the average intelligibility of each of the syllables was consistently higher (about 15% on the average)in the 3-alternative condition, but there was a strong correlation between the performance in the two response formats. In addition, the standard deviations of the percent correct scores are slightly smaller in the 3-alternative format. We plan to compare the two groups using performance indices that control for differences in chance level between the response formats, and also to compare the variability and the confusion matrices obtained under the two conditions.

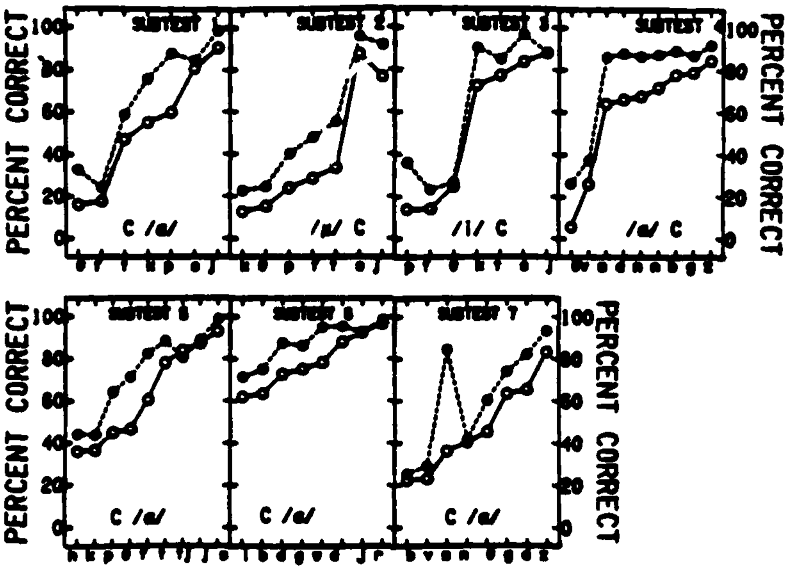

SUBTEST 1
SUBTEST 2
SUBTEST 3
SUBTEST 4
SUBTEST 5
SUBTEST 6
SUBTEST 7
PERCENT CORRECT
PERCENT CORRECT
PERCENT CORRECT
PERCENT CORRECT
0
20
40
60
80
100
C /a/
/a/ C
/i/ C
/a/ C
C /a/
C /a/
C /a/

Figure 6

III. AUDITORY ABILITIES OF HEARING- AND LANGUAGE-IMPAIRED PERSONS

Rate and number as limiting factors in the perception of sequences of syllables. **C. Watson, Espinoza-Varas.**

Listeners' abilities to process the details of sequences of sounds have been shown to be limited by two major factors: the number of components in the sequence, and the rate at which the components are presented. Individual differences in the ability to process large numbers of components, at high presentation rates have been proposed to account for certain language- or learning-related disabilities. Little attention has been paid to the possible interactions between these two factors, nor to the distribution of these abilities in the population of normal-hearing listeners. A test was developed to measure the effects of the number of syllables and, independently, those of syllable rate, on listener's abilities to process syllable sequences. The sequences consist of 2, 4, or 7 natural tokens of the spoken letters b, c, d, g, p, t, or v, produced as CV's ending in the vowel /i/. The duration of each token was edited to 75 msec. Syllable onset-to-onset times were 113, 178, 258 msec, yielding presentation rates of 8.9, 5.6 and 3.9 syllables per second. The listener's task was to transcribe the letters in each sequence, in a test format in which 180 sequences were presented, varying randomly in number and rate. Results for an initial test group showed some individual's performance to be more limited by rate than by number, and vice versa. Figure 8 shows data for 21 listeners collapsed over *position* and *letter*, for the medium rate. The functions relate the percent information transmitted with sequences of 2, 4, or 7 syllables, for each of the 21 subjects. It can be seen that some listeners show a much more severe drop when the number of syllables is increased from 2 to 4, than others. Basically, however, these "high capacity listeners" (those who do not show a marked change in performance as n is increased from 2 to 4) are also the ones who do the best on the shortest sequences, so we are not yet certain--despite our original conclusion that these letters are all more-or-less perfectly identifiable by all listeners--that the "high capacity" may not just be another reflection of accurate individual letter identification.

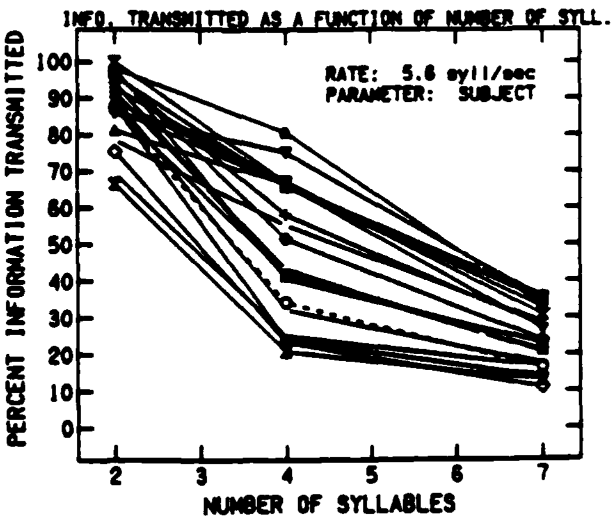


Figure 7

Manuscripts and Abstracts

Espinoza-Varas, B. & Watson, C.S. (1987). Informational limits in speech processing by normal and hearing impaired listeners. *J. Acoust. Soc. Am.*, 82, S42.

Frequency discrimination ability and stop consonant identification in normal hearing and hearing inpaired subjects. Ochs, Humes, Ohde, Grantham.

Identification of place of articulation in the synthesized stop-consonant-vowel syllables /bi/, /di/, and /gi/ was examined in three groups of listeners: (1) normal hearers, (2) subjects with high-frequency sensorineural hearing loss, and (3) normal-hearing subjects listening in noise. To examine the importance of the second formant (F2) transition in stop-consonant perception, stimuli with an appropriate F2 transition (called moving-F2 stimuli) were compared with stimuli in which F2 was constant (called straight-F2 stimuli). For straight-F2 stimuli, burst spectrum and F2 onset frequency were appropriate for the syllable involved. Syllable duration was also a variable, with durations of 10, 19, 28, and 44 ms employed. All subjects' identification performance improved as stimulus duration increased. Although the groups were equivalent in terms of their identification of /di/ and /gi/ syllables, the hearing impaired and noise-masked normal hearers showed impaired performance for /bi/, particularly for the straight-F2 version. No difference between moving- and straight-F2 versions was seen for /di/ and /gi/ stimuli. Second formant frequency discrimination measures were obtained, which suggest that subjects' discrimination abilities were not acute enough to take advantage of the formant transition in the /di/ and /gi/ stimuli. In general, the noise-masked normal listeners provided a good approximation of the performance of the hearing-impaired listeners.

Manuscripts and Abstracts

Ochs, M.T., Humes, L.E., Ohde, R.N. & Grantham, D. W. (in press). Frequency discrimination ability and stop consonant identification in normal hearing and hearing impaired subjects. *J. Speech Hear. Res.*

Modeling sensorineural hearing loss. I. Model and retrospective evaluation. Humes, Espinoza-Varas, C. Watson.

An internal-noise model for the evaluation of psychoacoustic data from the hearing impaired has been developed. The results obtained from the hearing impaired in several studies of frequency resolution, temporal resolution and speech recognition were compared to the results expected for noise-masked normal listeners. It is presumed in this approach that the hypothetical noise-masked normal listeners have masked thresholds that agree perfectly with the quiet thresholds of the hearing-impaired subjects. Using this approach, most of the results obtained from impaired ears on spectral-resolution and speech-recognition tasks can be accurately predicted; an exception being results from spectral-resolution paradigms using fixed-level signals. Some of the data from hearing-impaired listeners on temporal-resolution tasks, on the other hand, could not be adequately described with this approach. The latter data, however, are much more limited. Additional data are needed to better evaluate the adequacy of this approach in describing the performance of the hearing impaired on temporal-resolution tasks.

Manuscripts and Abstracts

Humes, L.E., Espinoza-Varas, B. & Watson, C.S. (1988) Modeling sensorineural hearing loss. I. Model and retrospective evaluation. *J. Acoust. Soc. Am., 83,* 188-202.

Models of the additivity of masking. Humes, Jesteadt.

Three models of masking additivity have been reviewed. These models are referred to here as the high-compression model (Penner, 1980), the power-law model (Lutfi, 1983, 1986), and a modified power-law model with compressed internal noise. While the high-compression model was derived from data for two or more nonsimultaneous maskers and the power-law model was derived from data for two or more simultaneous maskers, the modified power-law model assumes that the threshold in quiet is equivalent to a masked threshold resulting from an internal noise that is continually present. In addition, it includes assumptions concerning the interaction of two maskers prior to the addition of the masking effects. Most of the data on the additivity of masking can be accounted for with the modified power-law model, regardless of the nature of the maskers.

Manuscripts and Abstracts

Humes, L.E., & Jestaedt, W. Models of the additivity of masking. *J. Acoust. Soc. Am.* (submitted).

Further evaluation of a model of masking additivity. Jesteadt, Humes.

The model described above was evaluated retrospectively and appeared to provide an adequate description of a wide variety of data on the additivity of multiple maskers. In the present experiment, the model was evaluated prospectively. The masking of a 2000-Hz 20-msec probe tone presented 170 msec into a 200-msec masker was measured first for an 1800-Hz masker presented at 60 dB SPL. This is referred to as the "Masker 1 alone" condition (M1). Next, masking of this same signal was measured for "Masker 2 alone" (M2). Masker 2 was presented at each of several levels ranging from 40 to 80 dB SPL in 5-dB steps and was one of three frequencies: 1900, 1950 or 2100 Hz. The temporal relations between masker and signal were identical for both masker 1 and 2. Finally, masking was measured for both maskers combined.

Figure 8 shows some typical data for one subject and one Masker-2 frequency (1900 Hz). The horizontal dotted line shows the masking resulting from the fixed level 1800-Hz masker alone while the upward sloping line shows comparable data for the 1900-Hz masker alone. Circles indicate the masked thresholds for the combined masker. Finally, predictions of the modified power-law model are provided by the dashed-dotted line (without suppression) and the solid line (with suppression). The suppression incorporated in the model is *intermasker* suppression resulting from the concurrent presentation of both maskers during the combined-masker condition. The amount of intermasker suppression included varies with the relative levels and frequencies of the two maskers according to the rules outlined by Sach and Abbas. The modified power-law model with intermasker suppression provides a good description of these data as indicated in Figure 8. This also holds for other subjects and frequencies. This model of masking additivity is being explored further.

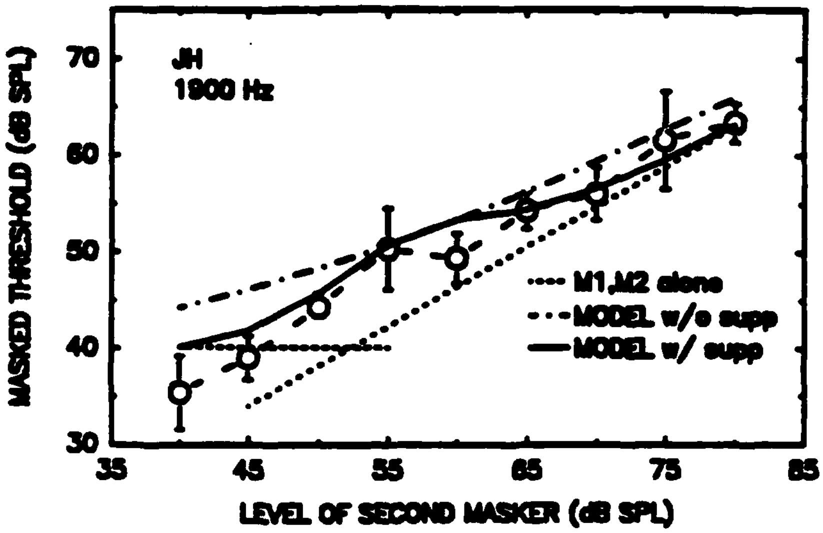

JH
1900 Hz
MASKED THRESHOLD (dB SPL)
70
60
50
40
30
35
45
55
65
75
85
LEVEL OF SECOND MASKER (dB SPL)
M1,M2 alone
MODEL w/o supp
MODEL w/ supp

Figure 8

TACTILE DISCRIMINATION

I. *Development of tactile arrays.*
Craig

One of the major obstacles to progress in the study of tactile sensitivity is the lack of a means to generate controlled, realistic tactile patterns. One way to generate such patterns may be through the construction of a new type of dense tactile array. A 13-element prototype for a dense tactile array was obtained from Johns Hopkins University. The frequency and amplitude characteristics of the individual drivers were evaluated. At low frequencies, 40 and 80 Hz, amplitudes in the range of 800 to 1000 microns peak-to-peak were obtained. At higher frequencies, lower amplitudes were obtained, for example, 250 microns at 250 Hz. Two major problems are currently being investigated, stiction and the physical mounting of the drivers to achieve the minimum spatial separation.

A second type of tactile array has been constructed using commercially-available stimulators. This 30-element tactile array is arranged in a 6-column by 5-row configuration that can be worn on a subject's arm. This array has been used as part of a tactile speech project. Using the array in conjunction with lip reading, subjects have shown significant improvement over lip reading alone in a tracking task.

II. *Interference in tactile localization.*
Craig

A series of experiments investigated the ability of subjects to localize a tactile stimulus in the presence of an additional, extraneous tactile stimulus. The subject's task was to localize a tactile stimulus (target) presented at one of several locations on his or her left index fingerpad. The target stimulus, generated on a 6 x 24 array of stimulators, was presented either by itself or in the presence of an extraneous stimulus (masker) that either preceded or followed the first stimulus. The localizability of the target was affected by the temporal separation between the target and masker in much the same way as previous studies had shown pattern identification to be interfered with. Presenting the masking stimulus to the same location as the target interfered with localizability, although not as much as presenting the masker to a different location. The results are discussed in terms of their implications for identification and discrimination of tactile patterns.

Manuscripts and Abstracts

Craig, J. C. (1987). Paper presented at Psychonomics Society, November.

Craig, J. C. (1988) Interference in tactile localizations. Submitted for publication.

VISUAL DISCRIMINATION

I. HUMAN PERIPHERAL VISION

Retinal factors which limit performance for pattern resolution and pattern detection.
Thibos, Cheney, Walsh, Still.

Sampling theory predicts that if the filtering effects of the eye's optical system are avoided, then visual resolution should be limited by the spacing of retinal sampling units, the so-called Nyquist limit. Since ganglion cells form a sparser array than do the photoreceptors, a stronger prediction is that visual resolution should vary with stimulus eccentricity from the fovea in accordance with the spacing between retinal ganglion cells. We have tested this theory experimentally by measuring resolution for sinusoidal grating stimuli formed directly on the retina as interference fringes, a technique which can produce gratings of nearly unit contrast independent of spatial frequency and optical focus. Quantitative comparison of the results with published data on retinal anatomy and physiology of the primate retina indicates that pattern resolution is limited by the spacing of primate beta ganglion cells, a class of neurons which provides the major retinal input to visual cortex, thus confirming the theoretical expectation.

A further prediction of sampling theory is that if retinal images contain spatial frequencies beyond the Nyquist limit, then these images will be undersampled and therefore will not be perceived veridically, a phenomenon called "aliasing." By using the interferometric stimulus, we are able to present such stimuli and so test the prediction experimentally. The results confirm that aliased patterns are detectable for the full range of spatial frequencies extending from the resolution (Nyquist) limit up to the finest pattern detectable by individual cone photoreceptors. Surprisingly, spatial integration over the receptive fields of ganglion cells does not appear to limit detection acuity.

Manuscripts and Abstracts

Thibos, L.N., Cheney, F.E. and Walsh, D.J. (1987) Retinal limits to the detection and resolution of gratings. *J. Opt. Soc. Amer.* A **4**, 1524–1529

Thibos, L.N., Walsh, D.J. and Cheney, F.E. (1987) Vision beyond the resolution limit: aliasing in the periphery. *Vision Res.* **27**, 2193–2197.

Cheney, F.E., Still, D.L., Thibos, L.N. and Walsh, D.J. (1987) What limits faithful encoding of spatial patterns in human peripheral vision? *J. Physiol.* **396**, 139P.

Thibos, L.N. and Still, D.L. (1988) What limits visual resolution in peripheral vision? *Invest. Ophthal. Vis. Sci.* **29** (suppl.), 138.

Walsh, D. J. and Thibos, L.N. Orientational anisotropy for resolution of gratings in peripheral vision. (in preparation)

Optical factors which limit performance for pattern resolution and pattern detection.
Thibos, Still, Cheney.

The optical system of the eye presents a low-pass filter at the front end of the visual system and thus represents a potential limiting factor for any visual task. Optical limitations are especially

likely in the peripheral field because of the presence of off-axis aberrations. Having identified the retinal limits to performance when optical factors are avoided with the interferometer stimulator (see above), the next logical step was to re-introduce the optical apparatus of the eye by using ordinary test stimuli (e.g. CRT display). Results indicate that resolution acuity outside the fovea is unaffected by the introduction of the eye's optical system. This proves that,for natural viewing conditions, peripheral resolution is determined by neural, not optical, factors. The results further showed that perceptual aliasing exists for natural viewing when the stimulus frequency is higher than the Nyquist limit of the retinal network. Thus we have established conclusively that vision beyond the resolution limit occurs under natural viewing conditions in peripheral vision.

The highest detectable spatial frequency for natural viewing was found to be less than that found for interferometric viewing. We conclude from this result that optical filtering becomes increasingly important as spatial frequency increases and, in the limit, it is optical quality that becomes the dominant factor that determines detection acuity. Because of the anisotropic nature of off-axis optical aberrations, we may further predict that detection acuity should vary with stimulus orientation and be maximal when grating stimulus is radially oriented. This prediction was confirmed experimentally and found to be of the same order of magnitude expected on the basis of optical theory

(see below).

Manuscripts and Abstracts

Cheney, F.E. and Thibos, L.N. (1987) Orientation anisotropy for the detection of aliased patterns by peripheral vision is optically induced. *J. Opt. Soc. Am.* A4, P79.

Still, D.L. and Thibos, L.N. (1987) Detection of peripheral aliasing for gratings seen in Newtonian view. *J. Opt. Soc. Am.* A4, P79.

Thibos, L.N., Still, D.L. Optical and neural factors limiting resolution acuity and detection acuity across the visual field. (in preparation).

Cheney, F.E. and Thibos, L.N. Orientational anisotropy for detection of gratings in peripheral vision. (in preparation).

Clinical disorders which limit performance for pattern resolution and pattern detection.
Bradley, Thibos

An important goal of visual science is to account for the loss of visual performance accompanying clinical disorders. Amblyopia is an example of a visual disorder which is characterized by a loss of visual acuity for no apparent reason. Although the subject of much research amblyopia remains a puzzle. As a result of our effort to identify those retinal and optical factors that limit resolution and detection of gratings, we have proposed a new hypothesis that may help to understand the mechanism of amblyopia. Our hypothesis is that the loss of acuity may be caused by an abnormally low density of neurons in the retina or later stages of the visual pathway that leads to undersampling, and thus aliasing, of spatial frequency components that normal individuals are able to resolve. Experimental tests of this idea are underway.

Manuscripts and Abstracts

Bradley, A. and Thibos, L.N. (1987) Amblyopia: Aliased vision through undersampling. *Amer. J. Optom. Physiol. Optics* 64, 105P.

Bradley, A and Thibos, L.N. (1988) Perceptual aliasing in human amblyopia. *Invest. Ophthal. Vis. Sci.* 29 (suppl.), 76.

II. HUMAN VISUAL OPTICS

Theory of ocular chromatic aberration.
Thibos, Bradley, Zhang, Still, and Howarth.

As a result of our finding that detection acuity in peripheral vision is limited by retinal image quality, it has become apparent that to fully appreciate the limits to visual performance requires an understanding of off-axis optical performance of the human ocular system. Although several of the chief optical aberrations which affect peripheral vision have been studied by others, no thorough assessment of ocular chromatic aberration has previoulsy been attempted. To fill this gap, we began by developing the theory of ocular chromatic aberration through analysis of a simple model of the eye's optical system. The goal was to devise a realistic model capable of making explicit, quantitative predictions suitable for experimental testing.

Our theoretical development has provided for the first time a unified treatment of both the transverse and longitudinal components of ocular chromatic aberration. This was achieved through analysis of a model eye consisting of a volume of water with a single, spherical refracting surface and an internal aperture. An important conceptual result of the analysis was the identification of a new reference axis, called the achromatic axis, which is of crucial importance in specifying the magnitude of transverse chromatic aberration. We call the angle between the achromatic and visual axes Ψ (the Indiana University logo) and have shown that this angle is the primary determinant of how much transverse chromatic aberration is present for foveal vision.

Chromatic aberration of the eye reduces image contrast for two reasons. First, the longitudinal aberration defocuses the image by an amount which varies with wavelength. Second, the transverse aberration induces a phase shift that varies with wavelength which also results in a loss of contrast. On the basis of this model we have computed the expected loss of image contrast for peripheral stimuli located anywhere in the visual field. The results are presented as a family of optical transfer functions parameterized by stimulus eccentricity and orientation.

We have also analyzed the performance of the interferometric stimulator we used in the peripheral vision experiments described above. This is one example of how the model eye can be used to solve applied problems. Although the results for natural viewing are more relevant to everyday visual performance, the interferometer results are especially convincing because this stimulator is insensitive to aberrations of focus (astigmatism, refractive error) and so isolates the chromatic aberration effect for experimental study.

Manuscripts and Abstracts

Thibos, L.N. (1987) Calculation of the influence of lateral chromatic aberration on image quality across the visual field. *J. Opt. Soc. Amer.* A 4, 1673–1680.

Thibos, L.N., Bradley, A., Still, D.L., Zhang, X. and Howarth, P.A. Theory and measurement of ocular chromatic aberration. (submitted to *Vision Res.*).

Thibos, L.N., Still, D.L. and Bradley, A. (1987) The relationship between transverse and axial chromatic aberration of the human eye. *Amer. J. Optom. Physiol. Optics* 64, 59P.

Thibos, L.N., Bradley, A., Still, D.L. and Henderson, P. (1987) Do white-light interferometers bypass the eye's optics? Clinical implications of decentering the optical beam in the pupil. *Optical Society of America Technical digest: Topical meeting on noninvasive assessment of the visual system*. 80–82.

Measurement of ocular chromatic aberration. Thibos, Bradley, Zhang, Still, and Howarth.

The model of ocular chromatic aberration developed above makes quantitative predictions about the magnitude of both the transverse and longitudinal chromatic aberration of the eye. Although measurements of the longitudinal component are available in the literature, no useful measurements have been reported for the transverse component. To fill this gap, we devised an experimental method for measuring transverse chromatic aberration based on a two-color, vernier-alignment task.

The results closely followed theoretical predictions thus supporting the postulated model. Unexpectedly, our measurements indicate that angle Ψ is nearly zero in the majority of subjects. The implication of this result is that, although the eye has substantial chromatic aberration, the pupil is positioned so as to minimize the transverse component of the aberration for central vision, thereby optimizing image quality for foveal viewing of polychromatic objects.

Additional experiments on a population of aging individuals has indicated that, contrary to previous reports, the magnitude of chromatic aberration does not vary significantly with age.

Manuscripts and Abstracts

Thibos, L.N., Bradley, A., Still, D.L., Zhang, X. and Howarth, P.A. Theory and measurement of ocular chromatic aberration. (submitted to *Vision Res.*)

Howarth, P.A., Zhang, X., Bradley, A.B., Still, D.L. and Thibos, L.N. (1988) Does the chromatic aberration of the eye vary with age? *J. Opt. Soc. Amer.* (in press).

Bradley, A., Still, D.L. and Thibos, L.N. (1987) Measurement of transverse chromatic aberration of the human eye. *Vision*: *Coding and Efficiency. A symposium for H.B. Barlow.*, P2.3

Thibos, L.N., Still, D.L. and Bradley, A. (1987) Psychophysical determination of the magnitude of lateral chromatic aberration in the human eye. *Invest. Ophthal. Vis. Sci.* **28** (suppl.), 218.

Bradley, A., Howarth, P., Thibos, L.N., Still, D. L. and Zhang, X.X. (1987) Chromatic abberration is independent of age. *Invest. Ophthal. Vis. Sci.* **28** (suppl.), 218.

Howarth, P.A., Bradley, A., Thibos, L.N., Still, D.L. and Zhang, X.X. (1987) Is chromatic aberration independent of age? *Amer. J. Optom. Physiol. Optics* **64**, 58P.

Effect of ocular chromatic aberration on visual performance.
Thibos, Bradley, Zhang, Still, and Howarth.

If the contrast of the retinal image is reduced because of chromatic aberration, as we have argued above, then visual performance should suffer. We have tested this idea four ways. First, we measured the loss of resolution acuity of foveal vision for white gratings viewed normally and second when the grating is produced interferometrically. In both cases acuity dropped about three-fold when

measured the loss of resolution acuity of foveal vision for white gratings viewed normally and second when the grating is produced interferometrically. In both cases acuity dropped about three-fold when the entrance pupil was displaced from its normal location near the achromatic axis to a point near the margin of the iris. In the third experiment we tested for orientational anisotropy with natural viewing and again in a fourth experiment using the interferometer. In each case the qualitative predictions were verified and found to be of about the same magnitude as expected from the quantitative predictions of the water eye model.

Manuscripts and Abstracts

Zhang, X., Bradley, A., Thibos, L.N., and Still, D.L. The effect of transverse chromatic aberration of the eye on visual acuity (in preparation)

Cheney, F.E. and Thibos, L.N. (1987) Orientation anisotropy for the detection of aliased patterns by peripheral vision is optically induced. *J. Opt. Soc. Am.* A4, P79.

Correction of ocular chromatic aberration to improve visual performance.
Thibos, Bradley, Zhang, Still, and Howarth.

One possible way to avoid the deleterious effects of ocular chromatic aberration is to correct the aberration with external optical lenses. The idea is to introduce an equal but opposite aberration which cancels the eye's aberration. Although such achromatizing lenses do an acceptable job of correcting the longitudinal component of ocular chromatic aberration, they may introduce extra transverse chromatic aberration. The net result can be an overall loss of image quality. We have calculated that one well-known lens design will magnify the transverse aberration fivefold. Experimental measurements confirmed the prediction. We conclude that in many applications the penalty of increased transverse aberration introduced by the achromatizing lens will greatly outweigh any benefit from correction of the longitudinal aberration.

Manuscripts and Abstracts

Zhang, X., Bradley, A. and Thibos, L.N. (1988) Achromatizing lenses may increase chromatic aberration in the retinal image. *Invest. Ophthal. Vis. Sci.* **29** (suppl.), 446.

PUBLISHED MANUSCRIPTS

1. Thibos, L.N. Walsh, D.J. and Cheney, F.E. (1987) Vision beyond the resolution limit: aliasing in the periphery. *Vision Res.* 27, 2193-2197.

2. Thibos, L.N., Cheney, F.E. and Walsh, D.J. (1987) Retinal limits to the detection and resolution of gratings. *J. Opt. Soc. Amer.* A 4, 1524-1529.

3. Thibos, L.N. (1987) Calculation of the influence of lateral chromatic aberration on image quality across the visual field. *J. Opt. Soc. Amer.* A 4, 1673-1680.

III. SPATIAL PROCESSING OF COLOR INFORMATION

Optical Transformations of Color Images.
Bradley, Thibos, Zhang

The human eye does not have an "achromatic" optical system. As described in the section on "Human Visual Optics" the human eye exhibits both axial and lateral chromatic aberrations. These aberrations pose a unique problem for images created from color-modulated stimuli. Previous analysis of the optical effects of chromatic aberrations have only been concerned with the effects they will have on images of luminance-modulated stimuli. We are currently developing a model to describe the optical attenuation and distortions specific to color-modulated patterns. Preliminary results indicate that large artifactual luminance modulations are likely to be present in the retinal images of nominally isoluminant color-modulated patterns. We are using these results to develop a method of generating truly isoluminant retinal images.

Manuscripts and abstracts

Bradley, A., Zhang, X.X., and Thibos, L.N. (1988) Retinal image isoluminance is compromised by lateral and longitudinal chromatic aberration. *J. Opt. Soc. Am.*, Annual Meeting, October 29 - Nov. 4, 1988.

Development of a High Resolution Color Stimulus Display Facility.
Bradley, Guth

In order to examine the performance capabilities of human color vision we have developed a general purpose high resolution image processing display system. Earlier optical technology used to produce accurate and sensitive control of color cannot provide the necessary control of spatial information that is essential for the study of human spatial vision. Modern color video technology has provided the vehicle to incorporate high resolution spatial images and high resolution color control. We have constructed a system based on the PDP 11-73 and the Adage 3000 that provides a 1000 by 1000 pixel array, and up to 1000 luminance levels for each RGB gun. We can select colors from a palette of 1 billion and independently control the luminance of 3 million pixels on each frame of the display. We are currently testing control software for this system and expect it to be operational by January 1, 1989.

Psychophysical Studies of Spatial Processing of Color Information.
Bradley

Most of what we know about the human visual system's ability to resolve, discriminate, and identify spatial patterns is restricted to spatial information described by intensity changes. Very little is known about our ability to process spatial information described by color changes. I have completed several collaborative studies with colleagues from the University of California at Berkeley on spatial masking and adaptation of color patterns. The spatial selectivity found for luminance modulated patterns was also observed for color modulated patterns indicating an important role for color in spatial vision. Future experiments on our own color video system will examine spatial resolution and dis-

crimination for isoluminant color stimuli. Our models of the eye's optical transformations will allow us to isolate psychophysical results that can be attributed to luminance artifacts in the retinal image.

Manuscripts and Abstracts

Bradley, A., Switkes, E., and De Valois, K.K. (1988) Orientation and spatial frequency selectivity of adaptation to color and luminance gratings. *Vision Research*, **28**, 841–856.

Switkes, E., Bradley, A., and De Valois, K. K., (1988) Contrast dependence and mechanisms of masking interactions among chromatic and luminance gratings. *J. Opt. Soc. Am.*, **A 5**, 1149–1162.

III. PERCEPTION OF MOVING OBJECTS

Identification of Static and Dynamic Targets Independent of Eye Movements.
Roth, Shiffrin

Are moving objects or characters identified by different laws than static stimuli? Letter stimuli were moved across the retina, varying speed, luminance, and distance traversed, in times such that eye movements were not possible, and identification judgments collected. Four experiments demonstrated decrements in identification performance for dynamically presented stimuli compared to static stimuli. Lateral inhibition and temporal masking seem able to account for many of the effects.

Publications and Abstracts

Roth, M. (1988) Master's thesis, Indiana University

III. COLOR THEORY
Guth

Although systematic research and theorizing has characterized the field of color vision for over a century, a quantitative model that can explain all of the major data about human color vision has not yet been developed. This is not to say that broad outlines regarding the basic form that a successful theory must take are not available, for certain properties of the physiological mechanisms that mediate human color vision have been well established. For example, the absorption characteristics of the three cone pigments are known within limits that are acceptable for almost all applications of a model, and it is almost certain that the theory will take the form of an opponent process theory. Within that framework, however, a great many possibilities exist in regard to the kinds of interactions that obtain among receptor and postreceptor mechanisms, and in regard to the kinds of mathematical functions that describe the input/output relationships at every stage of the theory.

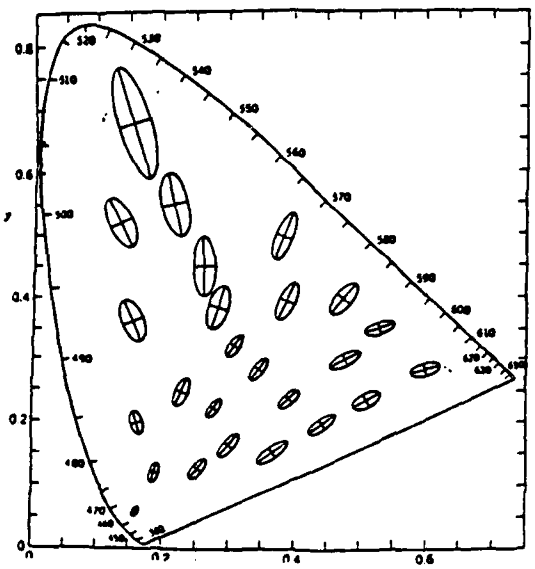
The problem is of general importance, for the design of lighting systems of any sort and the design of machine (or robotic) vision systems require that engineers understand how human beings will perceive, discriminate, and detect chromatic lights given the physical description of light arriving at the eye. An examination of existing models for color vision, including my own, will reveal that there is a tendency toward ever-increasing complications, in the sense that theorists are introducing more and more parameters at each stage of their models. It may, of course, be true that color vision is mediated by a very complicated system, but it is also true that the models become complicated because we

have not yet hit upon the key ideas that will allow relative simplicity to emerge from what sometimes seem to be hopelessly complex models.

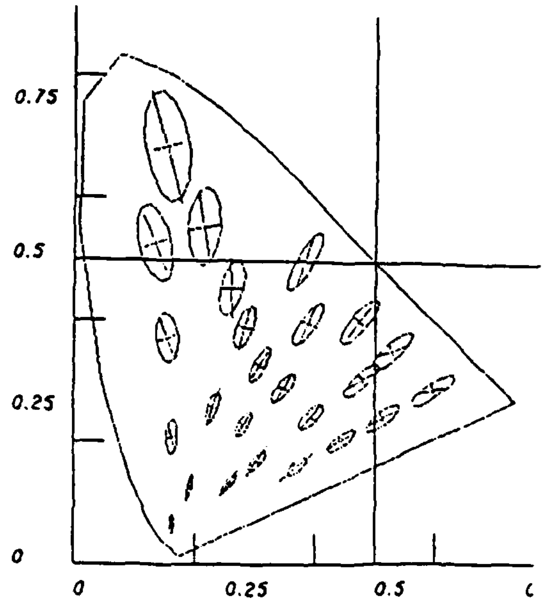
It appears as though we have developed a simple but very powerful model, based on work that has been completed since this portion of the project began. Briefly, the modes has, as its first stage, the Smith and Pokorny estimates of the absorption characteristics of the three cone types. At this stage there is a von Kries-like gain control system that reduces the neural output of each cone type as light intensity increases. The next stage of the model is very similar to the earlier successful model developed by my associates and me. This stage is seen as mediating detection responses, which require maximum possible neural information from all mechanisms. The subsequent stage recombines information from the second stage in such a way as to maximize not detection or magnitude judgments, but rather color discriminations and appearances that constitute the major job of perception at suprathreshold levels.

The range of predictions provided by the model surpasses any that has ever been published. It attends to almost all of the major phenomena of color vision, ranging from threshold-level spectral sensitivity and heterochromatic additivity data through suprathreshold color discriminations and hue appearances (and hue shifts) to effects of chromatic adaptation. Furthermore, it provides predictions of some data that have never before been accounted for by quantitative theories.

Space limitations do not permit a full application of all the model's predictions. What follows are some well-known color vision data with the theoretical predictions from the model.

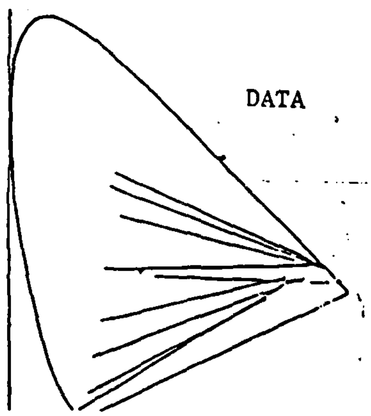


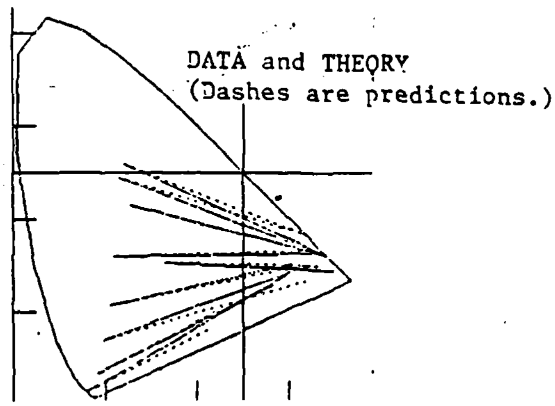
DATA (crosses)
(Ellipses are drafted by hand



DATA and Theory
(Ellipses are projections of constant diameter circles from the new model)

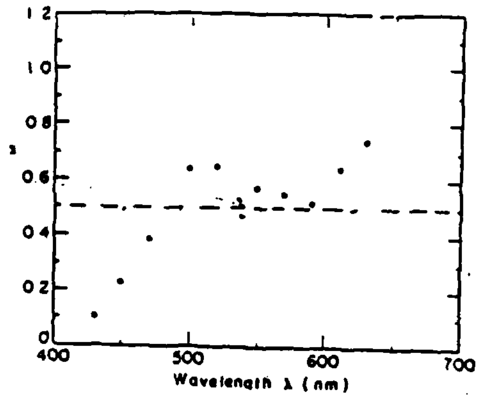
MacAdam (1942) ellipses (observer PGN) plotted in CIE 1931 (x, y)–chromaticity diagram. The axes of the plotted ellipses are 10 times their actual lengths.





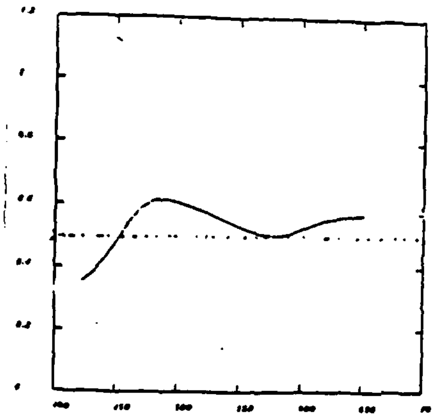
(Line endpoints appear identical after their adaptations.)

Corresponding colors for adaptations to red light and artificial light.



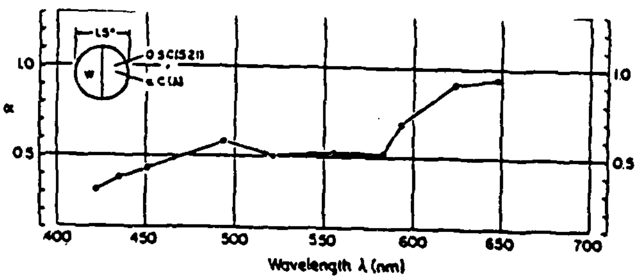
DATA

ABOVE: Additivity failures in heterochromatic brightness matching measured by Guth (1970) for nine observers. Solid dots: mean values. (Values show amounts of various wavelengths added to 0.5 white to yield unit brightness.)

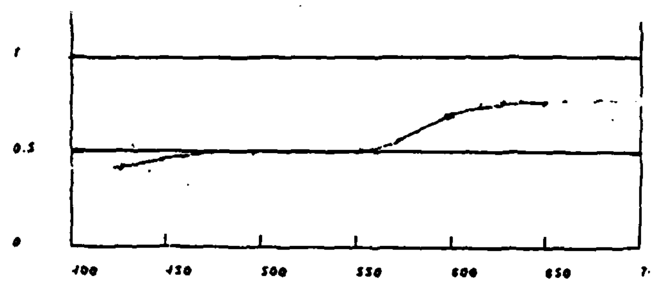


THEORY

(In these four graphs, values below 0.5 represent super-additivity, which is in short wavelengths for both data and theory.)



DATA



THEORY

Above: Mean results for nine observers of a direct heterochromatic brightness experiment conducted by Guth et al. (1969) to check the additivity law. If W is a fixed "white" reference stimulus, C(521) a monochromatic test stimulus of wavelength λ = 521 nm, $C(\lambda)$ a monochromatic test stimulus of wavelength λ (selected from a set of 10), and if C(521) brightness matches W and $C(\lambda)$ also brightness matches W, that is, $C(521) \overset{B}{=} W$, $C(\lambda) \overset{B}{=} W$; then $\alpha C(\lambda) + 0.5C(521) \overset{B}{=} W$ where α is equal to 0.5 if additivity holds. The experimental data indicate strong failure of additivity except for the trivial case of $C(\lambda) \equiv C(521)$.

MECHANISMS OF SONAR SIGNAL PRODUCTION AND VOCAL TRACT ACOUSTICS OF ECHOLOCATING BATS

I. Vocal Tract Acoustics of Echolocating Bats

The sound emission pattern and the acoustical role of the noseleaf in the echolocating bat, Carollia perspicillata.
Suthers, Hartley, D.J.

Carollia perspicillata (Phyllostomidae) is a frugivorous bat that emits low-intensity, broadband, frequency-modulated echolocation pulses through nostrils surrounded by a noseleaf. The emission pattern of this bat is of interest because the ratio between the nostril spacing and the emitted wavelength varies during the pulse, causing complex interference patterns in the horizontal dimension. Sound pressures around the bat were measured using a movable microphone and were referenced to those at a stationary microphone positioned directly in front of the animal. Interference between the nostrils was confirmed by blocking one nostril, which eliminated sidelobes and minima in the emission pattern, and by comparison of real emission patterns with simple computer models. The positions of minima in the patterns indicate effective nostril spacings of over a half-wavelength. Displacement of the dorsal lancet of the noseleaf demonstrated that this structure directs sound in the vertical dimension.

The Emission pattern of the echolocating bat, Eptesicus fuscus.
Suthers, Hartley, D.J.

The emission pattern of *Eptesicus fuscus* was found to be similar to those of the other FM bats studied in similar detail in that there is a mainlobe aimed forward of the animal together with a prominent -6 dB ventral lobe. This ventral lobe cannot be explained as the first sidelobe of a piston source mounted in an infinite baffle and must be formed by some other acoustic means. Nevertheless, a piston source with a radius comparable to that of the open mouth alone can explain the observed directionality. At wavelengths greater than the mouth dimensions, however, some additional sound "focusing" may occur, presumably due to diffraction by the head.

The acoustics of the vocal tract in the horseshoe bat, Rhinolophus hildebrandti.
Suthers, Hartley, D.J.

The transfer function of the supraglottal vocal tract of the horseshoe bat, *Rhinolophus hildebrandti* was obtained by a noninvasive technique, based on incremental variations in the helium content of inspired gas, which also allowed the source spectrum to be determined. The acoustic role of the vocal tract chambers was examined by obtaining the transfer function before and after filling the chambers. Simultaneous recording of sound pressures in the trachea during these experiments allowed some analysis of subglottal acoustics. With the vocal tract intact, the transfer function was found to show sharp transmission minima at the fundamental and third harmonic and a broad transmission maximum at the emitted second harmonic. This transfer function shape along with the source spectrum obtained, demonstrates that the second harmonic dominance in the emitted pulse is achieved by vocal tract filtering, although the source spectrum is different from that typical of man in that it does not show an f^{-2} harmonic decay. Changes in the transfer function caused by filling the nasal chambers suggest that these structures may play an impedance matching role at the second harmonic. Filling of the tracheal chambers did not affect the transfer function but changed the tracheal acoustics in a manner which suggests that these chambers may return backward-propagated sound to

the larynx with a phase shift. The possible interactive role of the nasal and tracheal chambers in increasing vocal efficiency at the second harmonic is posited.

Subglottal chambers in the horseshoe bat affect vocal efficiency.
Suthers, Hartley, D.J.

The horseshoe bat, *Rhinolophus hildebrandti*, emits sonar pulses containing a relatively long duration constant frequency component with most of its energy at the second harmonic. The laryngeal fundamental and higher harmonics are suppressed in the vocal tract. Rhinolophids emit sonar signals through their nostrils and their vocal tract contains enlarged nasal cavities and rigid tracheal chambers which have been postulated to act as acoustic filters. Suthers, Hartley and Wenstrup found, however, that filling these chambers has no effect on the frequency, intensity or spectrum of the emitted sonar signal. *Rhinolophus* appears to compensate for filling of the tracheal chambers by increasing the subglottal power to maintain a constant vocal output. The accompanying increase in glottal aperture may also increase the acoustic coupling between the sub and supraglottal portions of the vocal tract. In doing this the bat suffers a substantial decrease in the efficiency with which subglottal fluid power is converted to acoustic power (assuming the radiation pattern of the sonar pulse does not change). The tracheal chambers may therefore acoustically interact with the glottis to improve the vocal efficiency. A high vocal efficiency may be especially advantageous in these bats which produce long duration sonar pulses having a long duty cycle of phonation.

Acoustic role of tracheal chambers and vocal cavities in the horseshoe bat.
Suthers, Hartley, D.J., Wenstrup, J.J.

The acoustic role of the enlarged, bony, nasal cavities and rigid tracheal chambers in the horseshoe bat, *Rhinolophus hildebrandti*, was investigated by determining the effect of their selective filling on the nasally emitted sonar pulse and on the sound traveling backwards down the trachea.

Normal sonar signals of this bat contain a long constant frequency component with most energy in the second harmonic at about 48 kHz. The fundamental is typically suppressed 20 to 30 dB below the level of the second harmonic. None of the experimental manipulations described affected the frequency of the sonar signal fundamental.

Filling the dorsal and both lateral tracheal chambers had little effect on the emitted vocalization, but caused the level of the fundamental component in the trachea to increase 15 to 19 dB in most bats. When only the dorsal chamber or only the two lateral chambers were filled, the effect was less striking and more variable, suggesting that the tracheal fundamental is normally suppressed by acoustic interaction between these three cavities.

Filling the enlarged dorsal nasal cavities had no effect on the tracheal sound. The effect of this treatment on the nasally emitted sonar pulse was inconsistent. Sometimes the fundamental increased 10 to 12 dB, other times the intensity of all harmonics decreased; in still other cases the second, third or fourth harmonic increased,, but the fundamental remained unchanged.

When bats were forced to vocalize through the mouth, by sealing the nostrils, there was a prominent increase in the level of the emitted fundamental (10 to 21 dB) and in the fourth harmonic (6 to 17 dB). In one instance there was also a significant increase in the level of the third harmonic. The supraglottal tract thus filters the fundamental from the nasally emitted sonar signal, although the role of the inflated nasal cavities in this process in unclear.

We conclude that a high glottal impedance acoustically isolates the subglottal from the supraglottal vocal tract. The tracheal chambers do not affect the emitted sonar signal, but may attenuate the fun-

damental in the trachea and prevent it from being reflected from the lungs back towards the cochlea, via tissue conduction, along multiple indirect pathways which would temporally smear cochlear stimulation.

Tracheal and nasal chambers, by suppressing the internally reflected and externally radiated components, respectively, of the laryngeal fundamental, may enable horseshoe bats to rely on the tissue-conducted fundamental as a reference or marker of its own laryngeally generated sound which could be useful in processing sonar information.

Manuscripts & Abstracts

Hartley, D.J. & R.A. Suthers 1988. Directional emission and time precision as a function of target angle in the echolocating bat, *Carollia perspicillata*. In: P. Nachtigal (ed.) Animal Sonar: Process and Performance. Plenum Press. (In press)

Hartley, D.J. & R.A. Suthers 1988. Filter function of the supraglottal vocal tract and the acoustic role of the nasal and tracheal chambers in the horseshoe bat *Rhinolophus hildebrandti*. *J. Acoust. Soc. Amer.* (Accepted)

Hartley, D.J. & R.A. Suthers. The filter function of the supraglottal vocal tract and the acoustic role of the vocal tract chambers in the horseshoe bat. *Association for Research in Otolaryngology*. 11th Midwinter Research Meeting.

Hartley, D.J. & R.A. Suthers. 1988. The emission pattern of the echolocating bat *Eptesicus fuscus*. *J. Acoust. Soc. Amer.* (Submitted)

Hartley, D.J. & R.A. Suthers. 1987. The sound emission pattern and the acoustical role of the noseleaf in the echolocating bat, *Carollia perspicillata*. *J. Acoust. Soc. Am.* 82:1892–1900.

Suthers, R.A. & D.J. Hartley. 1988. Subglottal chambers in the horseshoe bat affect vocal efficiency. *Association for Research in Otolaryngology*. 11th Midwinter Research Meeting.

Suthers, R.A. & D.J. Hartley & J.J. Wenstrup. 1988. The acoustic role of tracheal pouches and nasal cavities in the production of sonar pulses by the horseshoe bat, *Rhinolophus hildebrandti*. *J. Comp. Physiol.* A162:799–813.

Dissertation

Durrant, G.E. 1988. Laryngeal control of the duration & frequency of emitted sonar pulses in the echolocating bat, *Eptesicus fuscus*. Ph. D. dissertation I.U..

II. PREDICTIVE TRACKING OF MOVING TARGETS BY ECHOLOCATING BATS.

Predictive tracking of horizontally moving targets by the fishing bat, Noctilio leporinus.
Suthers, Campbell, K. A.

We are conducting experiments on the pursuit strategy employed by the fish-catching bat, *Noctilio leporinus*. The results of these experiments, which were conducted with moving disappearing targets, suggest that these bats may predict the point of target interception.

In our experiments, *Noctilio* was trained to catch food moving at a constant velocity across the surface of a pool in a large laboratory flight room. Each trial consisted of a single flight along the length of the pool in which the bat dipped its feet at a target moving, towards the left or towards the right, across the pool. As the bat approached the target it broke two beams of light. The first light beam was located about a meter before the target, the second was located above the target. On some randomly selected trials, breaking the first beam activated a solenoid which pulled the moving target beneath the surface of the water in less than 30 msec. Simultaneously a strobe flash was fired on a camera at the end of the pool in front of the bat, providing an image on film of the position at which the target disappeared and the position of the bat. The bat broke the second beam of light when it was in the act of dipping so that a double exposure was obtained in which the second set of images showed the position of the dip relative to the submerged target. *Noctilio* continue to dip their feet at targets that disappear within a range of about 1 m..

The question which we have asked in these experiments is "Does *Noctilio* dip its feet to catch the target at the position where it was last detected or does it allow for continued motion by dipping ahead of the point where the target disappeared?" The former indicates a non-predictive tracking strategy while the latter suggests the possibility of predictive tracking. Control experiments eliminated the possible use of sounds produced by the moving target or cues from its wake. At each of three target velocities tested (66, 96 and 125 cm/s) the bat dipped ahead of the point where the target disappeared. Dips at fist moving targets were significantly ($p<0.05$) further ahead of the point of disappearance than were dips at slowly moving targets. There was no statistical difference between the accuracy of the dip relative to a submerged target and the accuracy for stationary disappearing control targets. This indicates that *Noctilio* was allowing for the differences in target velocity. The question of whether or not this behavior constitutes true predictive tracking is addressed in the proposed research.

One can easily imagine that fishing bats frequently encounter a ripple or the dorsal fin of a fish swimming at the surface, which disappears before the bat can catch it. An ability to allow for continued movement of the prey after it disappears might significantly improve the chances of catching food, since *Noctilio* is unable to echolocate submerged objects.

Manuscripts & Abstracts

Campbell, K.A. and R. A. Suthers. 1988. *Predictive tracking of horizontally moving targets by the fishing bat, Noctilio leporinus*. In: P. Nachtigall (ed.) Animal Sonar: Processes and Performance Plenum Press (in press).

III. PHYSIOLOGY OF BIRD SONG

Respiratory dynamics in a singing bird.
Suthers, Hartley, R. S.

Male canaries (*Serinus canaria*) produce songs of very long duration compared to the normal respiratory cycle. Each song consists of one or more phrases, with every phrase consisting of repetitions of a particular song syllable. Repetition rates for different syllables range from 3 to 35 notes per sec. We measured tracheal airflow and air sac pressure in order to investigate respiratory dynamics during song.

Song syllables (11–280 msec) are always accompanied by expiratory tracheal airflow. The silent intervals (15–90 msec) between successive syllables in a phrase are almost always accompanied by inspiration. Clearly, the five canaries we studied usually used the "mini-breath" respiratory pattern hypothesized by Calder (1970). Volumes expired and inspired are often similar to the dead space volume.

One of these birds occasionally used a pulsatile expiration pattern (Gaunt et al. 1973), where tracheal airflow ceased, instead of reversed during the silent intervals between successive syllables. Even though the volume of air expired per syllable was quite small, songs and phrases accompanied by pulsatile expiration were of much shorter duration than those accompanied by mini-breaths, their lengths presumably limited by the animal's finite vital capacity. Pulsatile expiration was used for only a few syllable types that were produced at higher repetition rates than syllables accompanied by mini-breaths. We suggest that male canaries switch to pulsatile expiration only when the syllable repetition rate is too high (greater than about 30 Hz) for them to achieve mini-breaths.

The syringeal membranes are abducted during the inspiratory phase of mini-breaths. During the sound producing portion of the expiratory phase, the membranes are partially adducted. Depending on the particular syllable in question, the syringeal membranes are either completely adducted or partially abducted prior to sound onset. Sound termination is accompanied either by adduction of the syringeal membranes or by the decrease of expiratory flow to zero prior to flow reversal for inspiration. During pulsatile expiration the syringeal membranes alternate between partial and complete adduction.

Regardless of which respiratory pattern is used, fluctuations in air sac pressure indicate that the level of thoracic compression always oscillates at the rate of syllable repetition. Clearly, both syringeal and respiratory muscles are precisely coordinated for song production.

Manuscripts & Abstracts

Hartley, R.S. and R.A. Suthers. 1988. Airflow & pressure during canary song: direct evidence for minibreaths. *J. Comparative Physiol. A.* (Submitted)

Schurr, R.L. and R.A. Suthers. 1987. Respiratory patterns during song production in the canary. *The Physiologist* 30(4):221.

Suthers, R.A. 1988. The production of echolocation signals by bats and birds. In: P. Nachtigal (ed.) Animal Sonar: Processes and Performances. Plenum Press. (In press)

Suthers, R.A. & D.H. Hector. 1988. Individual variation in vocal tract resonance may assist oilbirds recognizing echoes of their own clicks. In: P. Nachtigal (ed.) Animal Sonar: Processes and Performance. Plenum Press. (In press)

Multi-stage decision making. Robinson.

In this work we consider a person-machine system consisting of an automated alarm and a human monitor. The task of the human is to monitor a noisy channel on which information about a potentially dangerous condition may appear. The alarm system monitors an independently noisy channel for information about the same threatening condition. Using basic concepts of statistical decision theory, the Contingent Criterion Model of such a person-machine system has been developed. According to the model, the human should establish two criteria for responding: one contingent on an alarm from the automated detector and one, on no-alarm. The model shows large gains in performance compared to either detector alone. In Progress Report No. 1, we reported experimental support for the model. In the last two years, we have continued to develop the Contingent Criterion model, to investigate the effects of additional variables on the performance of the model, and to expand the model to include target identification.

A. *Effects of inter-channel correlation.* In our initial development of the Contingent Criterion Model, we assumed that the noise in the alarm-system channel is uncorrelated with that in the channel monitored by the human operator. Such an assumption is probably unrealistic. In the last year, we have investigated the degradation in performance that occurs with increased correlation between the two channels. The predictions of the model indicate that, although there may be a considerable performance decrement when the correlation is near unity, the model is quite robust, and system performance can exceed that of either detector alone even with correlations as high as 0.50.

B. *Effects of signal probability and values and costs.* Other parameters of importance in determining the performance of combined detection systems are the *a priori* probability of the signal and the values and costs of the possible outcomes of a decision. In our past work, we have evaluated system performance using measures derived directly from the Receiver Operating Characteristic (ROC), such as P(C) and d'. These measures are not affected by changes in *a priori* probability or values and costs. Thus, in the last year, we have turned to measures based on Expected Value. Analyses based on Expected Value suggest that the advantage of a multi-stage decision making system over a single-stage one is highly dependent on *a priori* probability and values and costs. In fact, under some circumstances a single-stage system should be used.

C. *Target identification.* We have begun to expand the Contingent Criterion Model to include signal classification (identification) as well as signal detection. This effort draws on the work of Nolte (JASA, 42, 773-777, 1967) Nolte and Jaarsma (JASA, 41, 497-505,1967), Green and Birdsall (Psych. Rev., 85, 192-206, 1978), and Starr, Metz, Lusted, and Goodenough (Radiology, 116, 533-538 ,1975). Our efforts to date suggest that the performance of a system consisting of a human operator and an automatic signal classifier can show significant improvement compared to either subsystem operating alone.

There are two important observations that may be drawn from this work. First, although combined system performance (human-plus-automated detectors) may be less than optimum with untrained operators, it is possible that human operators can be trained to use the available information more efficiently. A second observation is that system performance is dependent not only on the behavior (sensitivity and criterion placement) of the human operator and the criterion (threshold or alarm set-point) of the automated alarm system, but also on the *a priori* signal

probability and the values and costs. System performance may be altered by changing any of these parameters of the system. We feel strongly that the designers of automated alarm systems must take into account the complex interactions which may occur when human operators are involved.

All of the work on multi-stage detection systems was done in collaboration with Dr. Robert D. Sorkin of Purdue University. We take this opportunity to again acknowledge his many contributions to this, and other projects, both at ARL and HCL. Portions of the work described here have been reported previously [Sorkin and Robinson (N.T.I.S. Report No. DOT/OST/p-34/85/021, 1985) and Robinson and Sorkin (In Trends in Ergonomics/Human Factors II, Eberts and Eberts, North-Holland: Elsevier, 1985)]. Additional support for this work was provided by contracts with the U. S. Department of Transportation and with the U. S. Naval Weapons Center, China Lake, CA.

Manuscripts and Abstracts

Berg, B.G. (1987). Internal noise in auditory detection tasks. Ph.D. Dissertation, Indiana University.

Berg, B.G. & Robinson, D.E. (1987). Multiple observations and internal noise. *J. Acoust. Soc. Am.*, 81, S33

Fallon, S.M. & Robinson, D.E. (1987). The effects of decorrelation on the discriminability of noise samples. *J. Acoust. Soc. Am.*, 81, S33.

Sorkin, R.D., Robinson, D.E., & Berg, B.G. (1987). A detection theory method for the analysis of visual and auditory displays, Proceedings of the 31st Annual Meeting of the Human Factors Society, Vol. 2, 1184-1188.

Perception of multidimensional complex sounds.
Kidd, C. Watson, Washburne.

This project continues an investigation of listeners' abilities to categorize, or classify, complex sounds, based on information in three independent dimensions. Two aspects of multidimensional complex sound perception were examined: 1) the degree to which listeners can allocate attention simultaneously to three complex auditory dimensions, and 2) the ability to accumulate or integrate complex multidimensional information over a series of sound pulses.

Listeners were required to categorize stimuli as "targets" or "non-targets" on the basis of the stimulus values for each of three dimensions or features. The stimuli consisted of 1, 3, 5, or 7 sound pulses. Each pulse was 100 ms long with a 10-ms pause between pulses. The sound pulses (which are described in detail below) had three arbitrary features, and each feature could take on one of two possible values, designated as "target" and "non-target".

Since there were 3 binary features that identified a pulse as "target or "non-target", each individual pulse could have 0, 1, 2, or 3 *target* features. Optimal performance in this task (in terms of maximizing percent correct) could be achieved by counting the number of target features in each pulse and summing over pulses in the sequence. (Subjects were not specifically instructed to use this strategy, they learned to categorize the stimuli merely by listening for differences and attending to the feedback on each trial.)

The values for the features for each sound pulse in a sequence were selected probabilistically, so that the optimal performance level was kept constant at 90% correct for all sequence lengths. This was done by adjusting the overlap of the target and non-target distributions (the total number of target values) from which stimuli were selected. On each trial a stimulus was randomly sampled from either the "target" or "non-target" distribution. The overlap of the distributions is adjusted for each sequence length so that optimal performance is kept at 90% correct.

The individual sound pulses were synthesized by adding five simultaneous sinusoids. The three features of the sound pulses were ones that are important for the identification of many man-made or other single-source sounds. They were: 1) the relationships among the frequencies of the five sinusoids (*Harmonicity*), 2) the relative amplitudes of the sinusoids (*Spectral Shape*), and 3) the *Amplitude Envelope* of the entire waveform.

On the basis of pilot experiments, target and non-target properties were selected such that differences for all features were easy to detect and were approximately equal in discriminability. All stimuli were equated for RMS energy.

For the *harmonicity* feature, the target configuration was harmonic with components at successive integer multiples of the fundamental at 440 Hz. The non-target configuration was made *inharmonic* by a shift of the second spectral component from 880 to 740 Hz. For the *spectral shape* feature, the non-target configuration consisted of linearly decreasing amplitudes of successive components while the target configuration deviated from the monotonically decreasing spectrum in the form of an increased amplitude for the fourth component (with a compensating decrease in amplitude of the second and third components to maintain constant RMS energy for both configurations). The target configuration for the *amplitude envelope* feature was a 5-msec rise and decay time, with a 5-msec return to a lower amplitude after an initial burst. The non-target configuration was a 50-msec rise and decay time.

Subjects were told nothing about the nature of the differences between target and non-target stimuli. They were told that there would be two types of stimuli and each would tend to have certain characteristics, or qualities, that they would learn to recognize by listening carefully and attending to the feedback on each trial.

Subjects learned quickly and were within 10% of the 90% that the ideal observer could achieve for all sequence lengths by the end of the 10 sessions. They were able to integrate information over sequences of up to 7 pulses, with a uniform performance level of 80% correct.

Since it is possible to perform at this level with a variety of different patterns of attention to the three features (including attending to only one feature and ignoring the others), a test of attentional strategies was carried out. Correlations were computed, for all stimuli, between the number of target values for a given feature and listeners' responses. These correlations revealed that most subjects were paying *some* attention to each of the features, but most often with distinct preferences for certain features. In addition, the distribution of attention among the three features differed markedly across subjects.

To better determine the patterns of attention in the general population, a larger sample of subjects was tested in a shortened version of this experiment. Twenty seven audiometrically normal listeners were tested with single-pulse stimuli.

About the same number of listeners had a preference for each feature (eight preferred amplitude envelope, ten preferred spectral shape, and nine preferred harmonicity). For each of the

features, there were listeners with strong preferences for that feature and whose responses showed very low correlations with the other features. A few listeners showed substantial correlations with all three features. Overall, there were many substantially different patterns of allocation of attention to the three features, with little evidence of any clusters of listeners with similar patterns.

Relations between the feature–response correlations were examined for each of the three pairs of features. A similar range of correlations (from about 0.3 to 0.8) was found for each feature, and there is some evidence of tradeoffs between spectral shape and harmonicity, and between spectral shape and amplitude envelope. Response correlations with amplitude envelope and harmonicity, however, are essentially independent. The small negative correlations between weightings for two of the three pairs of features give some support to the hypothesis that performance is limited in terms of the *amount of information* the listener can extract from complex sounds.

To summarize, two conclusions concerning listeners' ability to categorize complex multidimensional sounds have been supported. One is that listeners can integrate information in sequences of sound pulses, with little or no loss of efficiency with increasing sequence length. The other is that although listeners' absolute efficiency in this task is fairly high, they are often not very good at allocating attention to all three features. In fact, comparable performance levels are achieved in spite of a variety of patterns of attention to the features of the stimuli. Additional studies of these abilities are being conducted.

Manuscripts and Abstracts

Kidd, G.R., & Watson, C.S. (1987). Perception of multidimensional complex sounds. *Journal of the Acoustical Society of America*, Suppl. 1, *81*, S33.

Differences between Visual and Memory Search: Implications for Models of Attention.
Czerwinski, Shiffrin

Automatism and attention involved in visual search for target letters is investigated. A number of theories are examined, including Fisher's Feature Overlap (1986; Fisher & Duffy, 1988), Treisman's Feature Integration Theory (e.g. Treisman & Gelade, 1980), Duncan & Humphrey's Resemblance Theory (1988) and Shiffrin, & Schneider's Automatism Theory (1977; Schneider & Shiffrin, 1977). Previous research has suggested the importance of 2 training paradigms: varied mapping (VM) and consistent mapping (CM). In consistent, but not varied mapping, automatic target detection appears to develop. However, previous research did not fully match CM and VM training conditions. Therefore, in all the experiments described, the amount of training on particular target–display combinations was equated between consistent and varied mapping training conditions. In Experiments One, Two and Three, when memory load was small, no consistent mapping advantage was seen. This may have been the result of subjects choosing to use optimal feature comparison sequences in both VM and CM conditions, when the load was small enough to permit such a strategy. However, when memory load was high, subjects came to rely on automatic search systems in consistent mapping, but not varied mapping conditions. The last experiment was carried out using a pure memory search task. A clear CM advantage in search emerged within the first session, even though the amount of training on CM and VM set and target combinations was equated. Also, this CM search advantage was observed using the same kinds of stimulus items which had not produced a CM advantage during pure visual search. The results of the four experiments are described within the framework of a hierarchical search model, in which stimuli are coded (using attention) to various levels, from featural to categorical. When responses

can be based on a strong association to the categorical level, due to consistent training, search can be carried out automatically. At the same time, efficient search can be based on comparisons made only at the featural level, when the load is small enough during search to allow such a strategy. When large loads or inconsistent training prevent responses based on one of these two levels during search, a limited capacity feature search must be carried out, often requiring serial comparisons through the display.Publications and Abstracts

Czerwinski, M. (1988) Doctoral dissertation, Indiana University.

Connectionist Approaches to Speech Perception

Robert F. Port, Dirk Van Gucht, John W. L. Merrill, Sven Anderson and Erich Smythe

This research program attempts to make a connectionist perceptual system that deals dynamically with continuously changing auditory inputs. Several prototype systems for dynamic acoustic signals have been developed here over the past year and a half. One system relies on hand-wired network fragments that use inputs to gate each other to extract useful features in the time domain. The other uses back-propagation learning to extract distinguishing features.

In the first project, a system known as SIREN for recognition of stop-vowel syllables was constructed by handwiring a set of mini-networks for identifying linear formant tracks (Smythe 1987, 1988). A battery of detectors was 'wired up' to detect various positive and negative formant slopes across the frequency range. Each slope detector was a 'veto inhibition network' that permitted strong activation if its inputs were excited in one direction but which was suppressed, or vetoed, if the excitation occurred in the wrong direction. The slope detectors inhibited their neighbors so that the most active slopes in each frequency range were stored in a line of delay nodes. Associative reward punishment learning (Sutton & Barto, 1981) was used to combine the slope descriptors and identify the stop. Using handmeasured formant tracks for 6 stops and 5 vowels from 5 speakers, the system could identify the syllables about 80% correct. Since the system was hand-constructed (and employed hand-measured formant tracks), this technique will obviously not scale up to much larger problems. The importance of SIREN, however, is that (1) it shows that information distributed over time can be integrated into a perceptual decision through use of several layers of delay nodes and inhibition-based detector systems, (2) it demonstrates the importance of allowing very low-level decisions to be made that depend on the local time-history of the input signal, and (3) the experiment helps clarify the many problems that must be solved in order to achieve a more general system.

A second approach to the stop-vowel syllable problem was also developed (Anderson, Merrill & Port, 1988) -- an approach that seems more promising for us to follow up. The SNET system is sequential in architecture, that is, there are at least 3 layers (Input, Hidden, and Output) but 4 cliques of nodes since the Output activations loop back to a set of State nodes that also feed the Hidden layer. The Input layer is fully connected to the Hidden layer which is fully connected to the Output layer. These connections are trained using backpropagation. Then, the activations of the Output layer are fed back (as inputs with weights of 1) to a clique of State nodes that provide the second set of inputs to the Hidden layer. The new activation of each state node is its input (from the Output nodes) plus its old activation decayed (with several State nodes at different decay rates for each Output node). Thus these nodes retain information about the recent history of the network output vectors. The Hidden layer, then, has learnable weights for both the Input node activations and for the history of network outputs. Since stimulation is provided one slice at a time, SNET needs this technique to 'remember' the stimulus history.

The stimuli were productions of the six syllables [ba,da,ga,pa,ta,ka] by 20 speakers. An FFT was performed every 5 ms and filtered into 35 1-bark frequency bands placed 1/2 bark apart, whose outputs were linearly compressed to the range [0,1]. Thus there were 35 realvalued inputs presented to the network every 5 msec. The target output signals were initially 0; but, after the stop burst, the target for the correct node rose linearly to +1 while the other 5 nodes fell toward -1. The error signal on each output node was propagated backward through the net on each time slice (using second-order backpropagation, Parker, 1987). The strongest output after reaching the end of the stimulus was taken as the network's "identification."

Performance on the best network (for 66 Input and State nodes, 66 Hidden-1, 12 Hidden-2 and 6 Output nodes) was 87% correct (after at least a million presentations of the training data). More important than the actual performance score (although it compares well with other speech recognition systems) are several characteristics of SNET. First, it is a network that behaves dynamically in time, integrating information from different points in time without 'representing' time directly. This is an important step forward since from the perspective of a nervous system, time is not simply another variable. It is the matrix within which both stimulus and response activity occurs. Second, if the vector of output activations (which are also the State node inputs) are submitted to cluster analysis for the temporal region just after the stop burst, it is found that they group themselves according to place-of-articulation while the voicing classes are random. This means that the system learned to identify place from the early acoustic input, to signal this information on the outputs, and to store the information in the State nodes until the information for voicing could be extracted and a final classification based on both place and voicing made. That is, the system learned to exploit information as it became available in time. Closely related to this observation is the fact that, despite the linearly ramped target function, the system preferred to dally around zero output for awhile, then make a rapid jump toward one of the 6 attractor states. Apparently, the dallying was 'purposeful' since the place of articulation was being coded during just this interval. Among the drawbacks of the system, however, are the fact that (a) the ramped target signal was quite arbitrary and unmotivated, and (b) the syllable onset was rigidly time-aligned with the stimulus onset, so the signal did not need to be 'monitored.'

Despite the impressive performance of SNET, the system needs to be 'smarter.' It should be able to 'wait' until it sees a target stimulus begin to be presented. As the system begins to track inputs over time and to discover that a pattern it has been trained on is underway, its categorial outputs should begin to move from neutral states and predict new input patterns. That is, a better system should exhibit rudimentary 'attention' and the ability to 'reset' when a local prediction is violated. This is one of the powerful features of the veto inhibition system in SIREN: one input can directly control the interpretation of another input. The drawback there was than the inhibition must be set up in advance by hand-design, rather that computed on a moment-to-moment basis.

Thus, in a series of recent pilot systems, the basic sequential architecture of the Anderson et al. system was modified by addition of 'Sigma-Pi' units (Rumelhart, Hinton, & McClelland, 1986) in the hidden layer. These use Input activations as multiplicative gates on the State nodes. Because the inputs to a Sigma-Pi unit are multiplied not just summed, one input can cancel the other input, or magnify it with either sign. The weights on the multiplicative input pairs can be trained with backpropagation. We have completed only preliminary experiments with the system but the results are promising. The net can be trained to respond whenever a particular signal occurs and to process patiently a white noise signal by continually resetting itself as long as necessary until the target appears. We believe a fully functional dynamic network for continuous processing of stimulus input can be approached in small steps by formulating significant tasks and incrementing the features of the system one step at a time.

Manuscripts & Abstracts

Anderson, Sven, John Merrill and Robert Port (1988) Speech analysis using sequential networks. G. Hinton, T. Sejnowski & D. Touretzky (eds.) *Proceedings of Carnegie-Mellon University Summer Institute on Connectionism*. (Morgan Kaufman, San Mateo, Cal.) 1988, In press.

Port, R., W. Reilly and D. Maki. (1987) Using global timing to discriminate words. *Journal of the Acoustical Society of America*, 83, 256-273.

Metcalfe, Janet and John Merrill. (1988) Conference Report: 1987 Conference on Dynamic Patterns in Complex Systems. *Psychobiology, 16*, 75–78.

Smythe, E. J. (1987) The detection of formant transitions in a connectionist network. *Proceedings of the First IEEE International Conference on Neural Networks*, (University of California, San Diego, 1987), pp. 495– 503.

Dorffner, Georg, Stan Kwasny & R. Port (1987) Parsing phonetic segments into syllables. In E. Buchberger & J. Retti (eds.) *Proceedings of the Third Austrian Artificial Intelligence Conference* (Springer-Verlag; Bonn), 49–63.

Dissertation

Smythe, Erich (1988) *Temporal Computation in Connectionist Models*. (Department of Computer Science, Indiana University, *Technical Report No. 251*.)

Accepted with Revisions

Merrill, J. W. L. & Robert F. Port (1988) A stochastic learning algorithm for recurrent networks. *Journal of Neural Networks*.

Use of Fault Trees.
Castellan

The use of fault trees in decision making and problem solving has been widely advocated in applied areas such as diagnostic trouble-shooting. However, research suggests that major problems occur when the fault tree is incomplete or an inappropriate representation of the task. People appear to be unable to adjust fault trees when confronted with an (properly or improperly) altered fault tree. Research in our laboratory is focusing on the reasons for this with the goal of developing procedures to enable users to identify and correct problem trees.

During the last year, one paper was published on this topic and a separate presentation was made at a professional meeting.

Hirt, E.R., & Castellan, N.J., Jr. (1988). Probability and category redefinition in the fault tree paradigm. *Journal of Experimental Psychology: Human Perception and Performance*, 14:122–131.

Hirt, E.R., & Castellan, N.J., Jr. (1988). Fault trees: Category redefinition and context. Paper read at *Midwestern Psychological Association*. Chicago.

Computer-Based Instruction.
Castellan

As the use of computer-based procedures for instruction grows, there is concomitant interest in the effectiveness of different methods. Surprisingly little research has been done comparing different methods. We have been conducting a series of experiments in an effort to compare drill-and-practice type tutorials with game-like software in introductory algebra. While game-like

software is believed to be beneficial in encouraging learners to spend more time-on-task, initial results show that when controlled for time-on-task, drill-and-practice appears to be more effective. One implication would be that in teaching motivated learners (typically adults) drill-and-practice may be the preferred instructional mode. It must be stressed that these results are tentative, and we shall be exploring factors of retention and transfer to new learning tasks among other factors. A paper is being prepared.

still working on this

CONSULTANTS AND VISITING SCIENTISTS

March 4-7, 1987 - Sue Dumais, Ph.D. of Bellcore for consultation and a lecture: "Retrieving information from humans and computers."

March 27-31, 1987 - Peter Howarth, Ph.D. from the School of Optometry, University of California, Berkeley for consultation and a lecture on "Pupil Dynamics: Fact and Fallacy" and a seminar on "Visual discomfort in VDT users."

April 2-3, 1987 - Robert Sorkin, Ph.D. of the Psychology Department of Purdue University for a lecture on "Likelihood Alarm Displays" and consultation.

April 22-23, 1987 - Ed Smith, Ph.D. of the Psychology Department of the University of Michigan for consultation and lectures.

May 18-19, 1987 - Hugh Wilson, Ph.D. of the Department of Physiological Sciences of the University of Chicago for consultation and to present seminars on "Masking and Pattern Discrimination in Human Vision" and "Pattern Discrimination in Development and Low Acuity Vision."

June 15, 1987 - Theodore E. Cohn, Ph.D. of the Physiological Optics Group of the University of California, Berkeley for consultation and a talk on "Theoretical limitations imposed by quantum fluctuations and the performance of real photoreceptors."

September 21-22, 1987 - Christopher Wickens, Ph.D. of the Department of Psychology and the Aviation Research Institute at the University of Illinois, Champaign-Urbana for consultation and to lecture on "Experimental Psychology and System Design," "Models of Multi-task Performance and Decision Making," and "Information Integration and the Object Display."

October 12, 1987 - Thomas S. Wallsten, Ph.D. of the Department of Psychology at the University of North Carolina at Chapel Hill for consultation and to present talks on "Understanding and Using Linguistic Uncertainties," and "Assessing the Risk to Young Children of Some Effects Associated with Elevated Blood-lead Levels: Example of a Method for Estimating Probabilities of Population Response Rates from Data and Judgments."

April 1, 1988 - Lola Lopes, Ph.D. of the Department of Psychology of the University of Wisconsin at Madison for consultation and to present a talk on "Risk Aversion and Rank Dependent Utility: A Psychological Perspective."

August 4, 1988 - Theodore S. Bell, Ph.D. of the UCLA School of Medicine for consultation and to present a seminar on "Interactive Factors in Consonant Confusion Patterns."

BIBLIOGRAPHY

The following is a cumulative list of articles published by Institute investigators from January 1, 1987 - August 31, 1988.

1987

1. Berg, B.G. (1987). Internal noise in auditory detection tasks. Ph.D. Dissertation, Indiana University.

2. Dorffner, Georg, Stan Kwasny & R. Port (1987) Parsing phonetic segments into syllables. In E. Buchberger & J. Retti (eds.) *Proceedings of the Third Austrian Artificial Intelligence Conference* (Springer-Verlag; Bonn), 49-63.

3. Espinoza-Varas, B. & Watson, C.S. (1987). Perception of complex auditory patterns by humans. In S.H. Hulse and R.J. Dooling (Eds.), *The Comparative Psychology of Complex Acoustic Perception* (in press).

4. Espinoza-Varas, B. (1987). Involvement of the critical band in identification, perceived distance, and discrimination of vowels. In M.E.H. Schouten (Ed.), *The Psychophysics of Speech Perception.* M. Nijhoff, The Netherlands, pp. 306-313.

5. Hartley, D.J. & R.A. Suthers. (1987). The sound emission pattern and the acoustical role of the noseleaf in the echolocating bat, *Carollia perspicillata. J. Acoust. Soc. Am.* 82:1892-1900.

6. Humes, L.E., Boney, S. & Loven, F. (1987). Further validation of the Speech Transmission Index (STI). *J. Speech Hear. Res.*, 30, 703-712.

7. Humes, L.E., Dirks, D.D., Bell, T.S. & Kincaid, G.E. (1987). Recognition of nonsense syllables by hearing-impaired listeners and noise-masked normal hearers. *J. Acoust. Soc. Am., 81,* 765-773.

8. Kewley-Port, D., Watson, C.S. & Cromer, P.A. (1987). The Indiana Speech Training Aid (ISTRA): A microcomputer-based aid using speaker-dependent speech recognition. *Synergy '87 Proceedings*, American Speech and Hearing Foundation, 94-99.

9. Kewley-Port, D., Watson, C.S., Maki, D. & Reed, D. (1987). Speaker-dependent speech recognition as the basis for a speech training aid. *Proc. 1987 IEEE Int. Conf. Acoustics., Speech, and Signal Processing*, Dallas, Texas, p. 372-375.

10. Port, R., W. Reilly and D. Maki. (1987) Using global timing to discriminate words. *Journal of the Acoustical Society of America*, 83, 256-273.

11. Schurr, R.L. and R.A. Suthers. (1987). Respiratory patterns during song production in the canary. *The Physiologist* 30(4):221.

12. Smythe, E. J. (1987) The detection of formant transitions in a connectionist network. *Proceedings of the First IEEE International Conference on Neural Networks*, (University of California, San Diego, 1987), pp. 495- 503.

13. Sorkin, R.D., Robinson, D.E., & Berg, B.G. (1987). A detection theory method for the analysis of visual and auditory displays, Proceedings of the 31st Annual Meeting of the Human Factors Society, Vol. 2, 1184-1188.

14. Thibos, L.N. (1987). Calculation of the influence of lateral chromatic aberration on image quality across the visual field. *J. Opt. Soc. Amer.* A 4, 1673-1680.

15. Thibos, L.N., Bradley, A., Still, D.L. and Henderson, P. (1987). Do white-light interferometers bypass the eye's optics? Clinical implications of decentering the optical beam in the pupil. *Optical Society of America Technical digest: Topical meeting on noninvasive assessment of the visual system.* 80-82.

16. Thibos, L.N., Cheney, F.E. and Walsh, D.J. (1987). Retinal limits to the detection and resolution of gratings. *J. Opt. Soc. Amer.* A 4, 1524-1529

17. Thibos, L.N., Walsh, D.J. and Cheney, F.E. (1987). Vision beyond the resolution limit: aliasing in the periphery. *Vision Res.* 27, 2193-2197.

18. Watson, C.S. (1987). Uncertainty, informational masking and the capacity of immediate auditory memory. In W.A. Yost and C.S. Watson (Eds.) *Auditory Processing of Complex Sounds*, Erlbaum Associates, Hillsdale, NJ.

19. Wilde, G. & Humes, L.E. (1987). Measurement of the attenuation characteristics of nonlinear hearing protective devices using the auditory brainstem response. *J. Acoust. Soc. Am.*, 81, 730-733.

20. Yost W.A. & Watson C.S. (Eds.) (1987). *Auditory Processing of Complex Sounds*, Erlbaum Associates, Hillsdale, NJ.

1988

21. Anderson, Sven, John Merrill and Robert Port (1988). Speech analysis using sequential networks. G. Hinton, T. Sejnowski & D. Touretzky (eds.) *Proceedings of Carnegie-Mellon University Summer Institute on Connectionism*. (Morgan Kaufman, San Mateo, Cal.) 1988, In press.

22. Bradley, A., Switkes, E., and De Valois, K.K. (1988). Orientation and spatial frequency selectivity of adaptation to color and luminance gratings. *Vision Research*, 28, 841-856.

23. Bradley, A., Zhang, X.X., and Thibos, L.N. (1988). Retinal image isoluminance is compromised by lateral and longitudinal chromatic aberration. *J. Opt. Soc. Am.*, Annual Meeting, October 29 - November 4, 1988.

24. Campbell, K.A. and R. A. Suthers. (1988). *Predictive tracking of horizontally moving targets by the fishing bat, Noctilio leporinus*. In: P. Nachtigall (ed.) Animal Sonar: Processes and Performance Plenum Press (in press).

25. Craig, J.C. (1988). Interference in tactile localizations. Submitted for publication.

26. Czerwinski, M. (1988). Doctoral dissertation, Indiana University.

27. Durrant, G.E. (1988). Laryngeal control of the duration & frequency of emitted sonar pulses in the echolocating bat, *Eptesicus fuscus*. Doctoral dissertation, Indiana University.

28. Hartley, D.J. & R.A. Suthers (1988). Directional emission and time precision as a function of target angle in the echolocating bat, *Carollia perspicillata*. In: P. Nachtigal (ed.) Animal Sonar: Process and Performance. Plenum Press. (In press)

29. Hartley, D.J. & R.A. Suthers (1988). Filter function of the supraglottal vocal tract and the acoustic role of the nasal and tracheal chambers in the horseshoe bat *Rhinolophus hildebrandti*. *J. Acoust. Soc. Amer.* (Accepted)

30. Hirt, E.R., & Castellan, N.J., Jr. (1988). Probability and category redefinition in the fault tree paradigm. *Journal of Experimental Psychology: Human Perception and Performance*, 14:122–131.

31. Howarth, P.A., Zhang, X., Bradley, A.B., Still, D.L. and Thibos, L.N. (1988). Does the chromatic aberration of the eye vary with age? *J. Opt. Soc. Amer.* (in press).

32. Humes, L.E. (1988). Selecting hearing aids for patients effectively (SHAPE). *Hearing Journal*, 41*(1)*, 15–18.

33. Humes, L.E., Espinoza-Varas, B. & Watson, C.S. (1988). Modeling sensorineural hearing loss. I. Model and retrospective evaluation. *J. Acoust. Soc. Am.*, *83*, 188–202.

34. Kewley-Port, D., Watson, C.S. & Foyle, D.C. (1988). Auditory temporal acuity in relation to category boundaries: Speech and nonspeech stimuli. *J. Acous. Soc. Am.*, 83 (3), 1133–1145.

35. Kidd, G.R., & Greenwald, A.G. (1988). Attention, rehearsal, and memory for serial patterns. *American Journal of Psychology*, 101, 259–279.

36. Leek, M.R. & Watson, C.S. (1988). Auditory perceptual learning of tonal patterns. *Perception & Psychophysics*, 43 (4), 389–394.

37. Metcalfe, Janet and John Merrill. (1988). Conference Report: 1987 Conference on Dynamic Patterns in Complex Systems. *Psychobiology*, 16, 75–78.

38. Roth, M. (1988). Master's thesis, Indiana University.

39. Suthers, R.A. (1988). The production of echolocation signals by bats and birds. In: P. Nachtigal (ed.) Animal Sonar: Processes and Performances. Plenum Press. (In press)

40. Suthers, R.A. & D.J. Hartley & J.J. Wenstrup. (1988). The acoustic role of tracheal pouches and nasal cavities in the production of sonar pulses by the horseshoe bat, *Rhinolophus hildebrandti*. *J. Comp. Physiol.* A162:799–813.

41. Suthers, R.A. & D.H. Hector. (1988). Individual variation in vocal tract resonance may assist oilbirds recognizing echoes of their own clicks. In: P. Nachtigal (ed.) Animal Sonar: Processes and Performance. Plenum Press. (In press)

42. Switkes, E., Bradley, A., and De Valois, K. K., (1988). Contrast dependence and mechanisms of masking interactions among chromatic and luminance gratings. *J. Opt. Soc. Am.*, A 5, 1149–1162.

Technical Reports and Abstracts of Papers Presented at Scientific Meetings

1987

1. Berg, B.G. & Robinson, D.E. (1987). Multiple observations and internal noise. *J. Acoust. Soc. Am.*, **81**, S33

2. Bradley, A., Howarth, P., Thibos, L.N., Still, D. L. and Zhang, X.X. (1987) Chromatic aberration is independent of age. *Invest. Ophthal. Vis..Sci.* **28** (suppl.), 218.

3. Bradley, A., Still, D.L. and Thibos, L.N. (1987) Measurement of transverse chromatic aberration of the human eye. *Vision: Coding and Efficiency. A symposium for H.B. Barlow.*, P2.3

4. Bradley, A. and Thibos, L.N. (1987) Amblyopia: Aliased vision through undersampling. *Amer. J. Optom. Physiol. Optics* **64**, 105P.

5. Cheney, F.E., Still, D.L., Thibos, L.N. and Walsh, D.J. (1987) What limits faithful encoding of spatial patterns in human peripheral vision? *J. Physiol.* **396**, 139P.

6. Cheney, F.E. and Thibos, L.N. (1987) Orientation anisotropy for the detection of aliased patterns by peripheral vision is optically induced. *J. Opt. Soc. Am.* A4, P79.

7. Fallon, S.M. & Robinson, D.E. (1987). The effects of decorrelation on the discriminability of noise samples. *J. Acoust. Soc. Am.*, 81, S33.

8. Howarth, P.A., Bradley, A., Thibos, L.N., Still, D.L. and Zhang, X.X. (1987) Is chromatic aberration independent of age? *Amer. J. Optom. Physiol. Optics* **64**, 58P.

9. Kidd, G.R., & Watson, C.S. (1987). Perception of multidimensional complex sounds. *Journal of the Acoustical Society of America*, Suppl. 1, **81**, S33.

10. Still, D.L. and Thibos, L.N. (1987). Detection of peripheral aliasing for gratings seen in Newtonian view. *J. Opt. Soc. Am.* A4, P79.

11. Thibos, L.N., Still, D.L. and Bradley, A. (1987). Psychophysical determination of the magnitude of lateral chromatic aberration in the human eye. *Invest. Ophthal. Vis. Sci.* **28** (suppl.), 218.

12. Thibos, L.N., Still, D.L. and Bradley, A. (1987). The relationship between transverse and axial chromatic aberration of the human eye. *Amer. J. Optom. Physiol. Optics* **64**, 59P.

1988

13. Bradley, A and Thibos, L.N. (1988). Perceptual aliasing in human amblyopia. *Invest. Ophthal. Vis. Sci.* **29** (suppl.), 76.

14. Guth, S.L. (1988). Color Theory. Abstract submitted SPSE/SPIE Symposium on Electronic Imaging. Jan. 15-20, 1989, Los Angeles.

15. Hartley, D.J. & R.A. Suthers. The filter function of the supraglottal vocal tract and the acoustic role of the vocal tract chambers in the horseshoe bat. *Association for Research in Otolaryngology*. 11th Midwinter Research Meeting.

16. Hirt, E.R., & Castellan, N.J., Jr. (1988). Fault trees: Category redefinition and context. Paper read at *Midwestern Psychological Association*. Chicago.

17. Smythe, Erich (1988). *Temporal Computation in Connectionist Models*. (Department of Computer Science, Indiana University, *Technical Report No. 251*.) 151 pages.

18. Suthers, R.A. & D.J. Hartley. (1988). Subglottal chambers in the horseshoe bat affect vocal efficiency. *Association for Research in Otolaryngology*. 11th Midwinter Research Meeting.

19. Thibos, L.N. and Still, D.L. (1988). What limits visual resolution in peripheral vision? *Invest. Ophthal. Vis. Sci.* **29** (suppl.), 138.

20. Zhang, X., Bradley, A. and Thibos, L.N. (1988). Achromatizing lenses may increase chromatic aberration in the retinal image. *Invest. Ophthal. Vis. Sci.* **29** (suppl.), 446.